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Tero Frondelius

DEVELOPMENT OF METHODS IN ENGINE DESIGN PROCESS

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY

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TERO FRONDELIUS

DEVELOPMENT OF METHODS IN ENGINE DESIGN PROCESS

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Abstract

This thesis promotes simulation-driven design process. It means, in practice, a fact-based methodology, where the project core team makes the design process decisions based on the simulated facts instead of gut feelings. At the same time, this thesis will, hopefully, work as introductory material for new employees, and parts of it work as teaching material in machine design courses. This thesis builds on knowledge gained from the practical work experience during the past twelve years while working in the Wärtsilä R&D and Engineering organization. All the method development exists because there has been a need for it. The results presented in this thesis are valuable to Wärtsilä, who has been the early adopter of the simulation-driven design process. In Wärtsilä's engine development projects the new presented methodology is in use. Wärtsilä-31 product was the first using the new methodology, and the results speak for itself, it is the most efficient 4-stroke engine in the world. Rest of the Finnish industry will benefit from the results as well. All of these new findings will eventually merge into the machine design teaching in the University of Oulu. Thus, the next generation designers will have the new set of tools when they enter the job market.

Keywords: engine development, simulation-driven design process

Frondelius, Tero, Menetelmäkehitys moottorin suunnitteluprosessissa.
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Tiivistelmä

Tässä väitöskirjassa esitellään simulointivetoista tuotekehitystä. Käytännössä se tarkoittaa, että projektin ydinryhmä tekee päätökset simulointituloksien perusteella vakiintuneiden käytäntöjen sijaan. Kuvaillut menetelmät perustuvat kahdentoista vuoden työkokemukseen Wärtsilän moottorien tuotekehitysosastolla. Väitöskirjan tulokset ovat arvokkaita Wärtsilälle, joka on jo varhain ymmärtänyt simulointivetoisen tuotekehityksen edut. Kaikki esitellyt menetelmät on kehitetty todelliseen tarpeeseen, ja ne ovat käytössä Wärtsilän uusien moottorien tuotekehitysprojekteissa. Wärtsilä 31 -moottori oli ensimmäinen tuote, jonka kehityksessä näitä uusia menetelmiä käytettiin, ja tuloksena syntyi maailman parhaalla hyötysuhteella varustettu moottori. Wärtsilä tulee käyttämään tätä väitöskirjaa uusien työntekijöiden perehdyttämismateriaalina, mutta myös muulla suomalaisella teollisuudella on mahdollisuus hyötyä sen tuloksista. Toivon mukaan väitöskirjassa esitellyt uuden menetelmät päätyvät ammattikorkeakoulujen ja yliopistojen koneesuunnittelun opetukseen ja antavat seuraavan sukupolven koneensuunnittelijoiden käyttöön nykyaikaiset työkalut, kun he astuvat työmaailmaan.

Asiasanat: moottorin kehitys, simulointivetoinen tuotekehitys

To my beloved Galina and Ariana

Acknowledgements

I would like to acknowledge my employer Wärtsilä for the opportunity to focus on the research. The main enabler has been my superior Mr. Hannu Tiehaara who has approved the time and money spent to this research. Secondly, I would like to acknowledge my supervisor professor Mauri Haataja for valuable discussions and encouragements as well as professor Jukka Kömi. Also, all my teammates, including externals, are warmly acknowledged, especially the ones who directly contributed to the research papers: Pasi Halla-aho, Antti Mäntylä, Juho Könnö, Thomas Resch, Maria Santos-Descalzo, Jukka Aho, Joona Vaara, Tom Andersson, Matti Lindroos, Tuukka Verho, and Anssi Laukkanen; are warmly acknowledged.

I would like to acknowledge my loving and supporting wife Galina who has been very understanding and supporting during the project. Finally, I hope my example will encourage my daughter Ariana to study hard.

List of abbreviations

3D	*Three Dimensional*
AVL	*AVL List GmbH*
CAE	*Computer-aided Engineering*
CAD	*Computer-aided Design*
CAM	*Computer-aided Manufacturing*
CEO	*Chief Executive Officer*
CFD	*Computational Fluid Dynamics*
CIMAC	*International Council on Compustion Engines*
DDP	*Digital Design Platform*
DOF	*Degrees of Freedom*
EHD	*Elastohydrodynamic*
FEA	*Finite Element Analysis*
FEM	*Finite Element Method*
FEV	*Forschungsgesellschaft für Energietechnik und Verbrennungsmotoren*
FFT	*Fast Fourier Transform*
Genset	*Generator set including combustion engine and generator*
HDF	*Hierarchical Data Format*
HP	*Hewlett-Packard*
IACS	*International Association of Classification Societies*
I.C.	*Internal Combustion*
M53	*Calculations for I.C. Engine Crankshafts*
MBS	*Multibody Simulation*
MPI	*Message Passing Interface*
NVH	*Noise Vibration Harshness*
PDM	*Product Data Management*
PLM	*Product Lifecycle Management*
R&D	*Research and Development*
RQ	*Research Question*
SA&D	*Structural Analysis & Dynamics*
SPDM	*Simulation Process and Data Management*
W6L32	*Wärtsilä six-cylinder inline engine with bore of 32 cm*
XDMF	*eXtensible Data Model and Format*
XML	*eXtensible Markup Language*

List of original publications

This thesis is based on the following articles, which are referred to in the text by their Roman numerals (I–VII):

I Frondelius T, Halla-aho P & Mäntylä A (2016) Crankshaft development with virtual engine modelling. In: CIMAC Congress Helsinki.

II Könnö J, Frondelius T, Resch T & Santos-Descalzo MJ (2016) Simulation based grid compliance. In: CIMAC Congress Helsinki.

III Frondelius T & Aho J (2017) JuliaFEM —open source solver for both industrial and academia usage. Rakenteiden Mekaniikka 50(3): 229–233. `https://doi.org/10.23998/rm.64224`. Open access.

IV Könnö J, Tienhaara H & Frondelius T (2017) Wärtsilä digital design platform. Rakenteiden Mekaniikka 50(3): 234–238. `https://doi.org/10.23998/rm.64621`. Open access.

V Frondelius T, Tienhaara H & Haataja M (2018) History of structural analysis & dynamics of Wärtsilä medium speed engines. Rakenteiden Mekaniikka 51(2): 1–31. `https://doi.org/10.23998/rm.69735`. Open access.

VI Frondelius T, Mäntylä A, Vaara J, Könnö J, Andersson T, Lindroos M, Verho T & Laukkanen A (2018) Micromechanical modeling of the role of inclusions in high cycle fatigue damage initiation and short crack growth. In: CAASE18 The Conference on Advancing Analysis & Simulation in Engineering. Nafems.

VII Frondelius T, Tienhaara H, Kömi J & Haataja M (2018) Simulation-driven development of combustion engines: theory and examples. SAE Technical Papers. ISSN: 0148-7191 `https://doi.org/10.4271/2018-01-5050`. Open access.

Tero Frondelius has been the main and corresponding author of the original research papers I, III, V, VI, and VII. He has designed and carried out the research in all papers, except in VI where all micromechanical work is carried out in VTT. In the original research paper II, where Santos-Descalzo has done the simulation work, he has a significant role in designing the research plan and preparing the manuscript. Finally, in the original research paper IV Frondelius has prepared the manuscript and has been tightly involved in the research work.

Contents

1 Introduction

1.1 Background and research environment

Traditional engine design builds on top of prototype engines, which are thoroughly tested in the engine laboratory. The development cycle of the traditional approach is slow, because all the changes need to have a detailed design including drawings and manufacturing details like CAM programs and moulds for castings. Motivation for this work comes from the speed up of the development process. This thesis enlightens the needed research in the engineering mechanics domain of the four-stroke medium speed engines to guarantee world-class product development. The need to increase fuel efficiency has been the driver of engine R&D, leading to increased cylinder pressure and overall higher stresses in the essential engine components.

An example engine used in this thesis is available from eight- to sixteen-cylinder arrangements and has a power output varying from 4.2 to 9.8 MW, with the engine speeds at 720 and 750 rpm. The sixteen-cylinder version length, width, and height are 9.0, 3.5, and 4.2 meters, respectively, and its weight is 89.0 tons. [1] Also, the example engine is the most efficient four-stroke diesel engine in the world. In addition, its modular design enables notable reductions in maintenance time and costs, thereby increasing power availability and reducing the need for spare parts. [1]

The maintenance interval of the medium speed marine engines is comparable to the designed lifetime of a car engine. According to [1], the maintenance interval of the engine is 8000 hours. As an example, a passenger car driven at an average speed of 25 km/h for the same duration of 8000 hours will amount to a total of 200 000 kilometers, which would be a respectable life for any car. The medium speed engine is designed to run at a 100% load continuously, which is another difference when compared to the car engines, which typically only use around 20% of power when driving 100 kilometers per hour.

All the above has been a driver for the simulation method development, in other words, the need to keep producing the reliable engine products. That is where this thesis gives the big picture and looks into the topic from the product development process perspective. Design Process of Engines, presented in Figure 1, follows the process of Eppinger and Ulrich's [2] machine design book quite closely. The process itself is very well-known, meaning that all machine design books such as Hubka and Eder [3], as well as Ullman [4], have it defined.

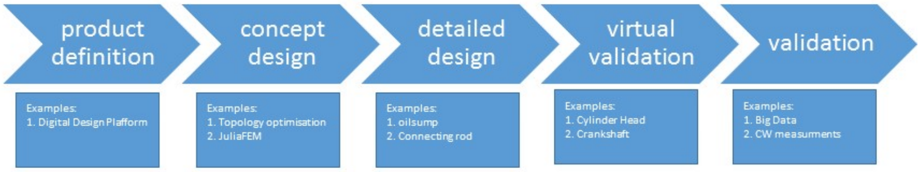

Fig. 1. Engine design process with the examples of engineering mechanics research of simulation-driven design. Reprinted by permission [VII].

The different phases of the design process gate model are product definition, concept design, detailed design, virtual validation, and validation. Figure 1 illustrates the structure and gives a list of examples used in the original research paper [VII]. These examples of the simulations, which have required some research and method development, answer the original research paper research question.

Before diving into the details, let us look at, in the form of a literature review, how other companies and researchers have been tackling the issue. Zimmermann et al. [5] describe a systematic system design methodology, especially from the uncertainty point of view, while Erlandsson [6] focuses on modal analysis. Both of these studies show the same main design phases. After these full models, let us look into some details.

Quite a significant feature in the design process is the systematic failure model simulations, like Löfstrand et al.'s [7] Partitioned Multi-objective Risk Method (PMRM). Then, Heikkinen and Müller's [8] design research methodology is applied to further develop the Engineering Workbench into a versatile design support system and expand the functionality to include producibility assessment. Both of these analysis tools are used for a different scale than detailed finite element method (FEM) simulations, as an example. The next paragraph will focus on more detailed simulations.

The base of the flexible multibody system are substructures, which are typically condensed using the Craig-Bampton method [9]. In Wärtsilä, these full engine flexible multibody system models are called as ”Virtual Engine”, describing that they are representing the full engine dynamics with realistic loading conditions, and these are multipurpose models which can be used for response analysis, load generation to nonlinear FEM, and engine acoustics. Next, the history of the flexible multibody usage in medium speed engine field is reviewed.

Already in 1998, Rassner et al. [10] showed how flexible Multibody System (MBS) could be used to calculate medium speed diesel engine crankshaft more accurately than using the IACS M53 approach [11, 12]. In the paper, they also made a comparison between the simulation and the measurements, and they concluded that correlation is statistically significant for both four- and five-cylinder engines, which they have used in their study. Same year Dahler et al. [13] concluded that numerical simulations are a handy tool in problem-solving. They modeled the full power train of the ship, although it was a simplified mass inertia model and also made the comparison to the measurements, which matched well.

In Wärtsilä, the first attempt to start using the flexible multibody dynamics in crankshaft calculations was made in 2003, when Savolainen [14] modeled W6L32 crankshaft by using the AVL Excite Power Unit [15]. However, full engine harmonic response calculations were introduced already in the year 2000 by Tienhaara et al. [16]. Methodology fine-tuning continued and was published first in [17] and followed in the CIMAC Congress in Vienna in 2007 [18].

In the same Congress, multiple papers of multibody system simulation in large engine development were presented. Trampert et al. [19] used FEV virtual engine to calculate fatigue of the integrated front-end component. They also made strain gauge measurements to validate the multibody system model. Sun et al. [20] studied crankshaft and main bearing wall flexibility and took the simulations to the next level by studying the elastohydrodynamic of the main bearings. Steffens [21] introduced NVH calculations by using the flexible multibody system model. He concluded that virtual NVH development tools are prerequisite for cost and time effective engine development concerning engine noise and vibration behavior. Finally, Naranca et al. [22] took it to the next level by modeling the whole ship using multibody system tool. They concluded that the advantage of the new methodology is the correct prediction of realistic excitation coming from engine and power train during engine operation. In Wärtsilä, around same time in 2005, Ylimäinen [23] studied the camshaft gear train noise. A more recent study from 2014 are Vaara's [24] thesis about engine cover noise modeling.

Seifert et al. [25, 26] studied the thermomechanical fatigue of the cylinder head, taking into account the nonlinear effects of plasticity. Their selected methodology is quite close to the one briefly discussed in this thesis section 2.3. Kuribara et al. [27] took it one step further and added the high cycle vibration loading simulated in multibody dynamics software. Ince [28] proposed an alternative methodology for nonlinear plasticity calculations for vehicle components by using Glinka's model, an evaluation of Neuber's rule. Munson et al. [29] highlight the importance of damping in a dynamic analysis to get the correct loading for fatigue analysis. Critical plane algorithms such as Findley and Dang Van have taken a firm position in the steel application fatigue analysis. Gaier et al. [30] used it for fatigue analysis of carbon composite laminates. Also, imperfection modeling has become more important to accurately estimate the fatigue lifetime and safety factor against infinite lifetime. Bleicher et al. [31] developed a model to use phased array ultrasonic inspection method to get the local material properties.

Conjugate Heat Transfer analysis is the basis of the engine thermal distribution and, therefore, a crucial step to defining thermomechanical fatigue loading. Cicalese et al. [32], as well as Bovo [33], studied the full engine model and its temperature distribution.

Big data analysis is becoming more and more common. Michlberger and Sutton [34] studied the low-speed pre-ignition and high knocking. Yanarocak and Boz [35] used the measurement data to design safe engine controls to protect the rocker arm. Yerra and Pilla [36] showed how data could be used in manufacturing to make it more efficient.

Karlberg et al. [37] did a comprehensive literature review of the state of the art in simulation-driven design in 2013, followed by Motte et al.'s [38] computer-based design analysis literature review in 2014, and again followed by an industrial survey of computer-based design analysis from Petersson et al. [39]. Sandberg et al. [40] stated: "Investigation and evaluations show that supporting tools and relevant information must be made readily available, intuitive, integrated into the environment where they are needed and, ultimately, be perceived as a natural part of daily development for them to be accepted and used." What do these mean in practice?

Three examples of the state-of-the-art simulation-driven design processes from literature are now presented: Larsson's [41] use of multi-body simulation (MBS) in product development process, Ahmad et al.'s [42] simulation-driven methodology for the design of haptic devices, and Sravan et al.'s [43] simulation-driven methodology of blank-holder. Moreover, Gouyou et al. [44] present tolerance analysis and use FEM distinctively in the flange example. Main improvement this paper brings to the state-of-the-art simulation-driven design process is the link between the high-level business requirement and the low-level validation requirements. Finally, simulation frameworks will conclude this literature study.

Saavedra et al. [45] suggest a knowledge-based framework, including a toolkit of simulation methods, as its principal element to combine simulations in the product development process. Petersson's [46] method is the use of templates to enable designers to make simulations. Further, Pavasson et al.'s [47] methodology requires an increased amount of multidisciplinary interaction to combine deterministic simulation and probabilistic simulation. Caridi et al. [48] remind to take into account how much to share information when outsourcing. Furthermore, Ahmed-Kristensen and Vianello [49] investigated the mechanisms involved in the transfer of knowledge between service and design. The findings showed an imbalance in the transfer of knowledge between engineering designers and service engineers, e.g., more than 50% of instances regarding knowledge from service were pushed (hence made available) to the engineering designers without them actively requesting this knowledge based on Ahmed-Kristensen and Vianello [49]. Lastly, Shao et al. [50] proposed the development of the uniform intermediate model that supports high fidelity and efficient visualization of multidisciplinary heterogeneous simulation data. As a conclusion, Könnö et al.'s [51] digital design platform answers to all these product development process needs. Further explanation can be found in section 3.4, as well as in [52, 53].

1.2 Objectives and scope

This thesis promotes simulation-driven design process in engine design. It means, in practice, a fact-based methodology where the project core team makes the design process decisions based on the simulated facts instead of gut feelings.

This thesis answers five research questions: 1) How open source software development enables better product design? 2) How revenue-based maintenance demands more accurate simulations methods? 3) When does an organization start to believe in virtual validation? 4) What enables the simulation-driven design process? 5) Why is accurate fatigue assessment essential in virtual validation?

Table 1. Mapping between research questions (RQ) and original research papers.

Research Question	I	II	III	IV	V	VI	VII
RQ1			X				X
RQ2		X					X
RQ3					X		
RQ4	X	X		X	X		X
RQ5	X					X	

Table 1 and Figure 2 show how the research question: What enables the simulation-driven design process? – is in the center where most of the other things link. Second central role goes to the research question: How revenue-based maintenance demands more accurate simulations methods? Research question: How open source software development enables better product design? – links to the others through the original paper [VII], which focuses on the simulation-driven design process, as the whole thesis. Research question: When does an organization start to believe in virtual validation? – links to the others naturally through the original paper [V], which is the history of the simulation method development. Finally, research question: Why is accurate fatigue assessment essential in virtual validation? – links to the others through the original research paper [I].

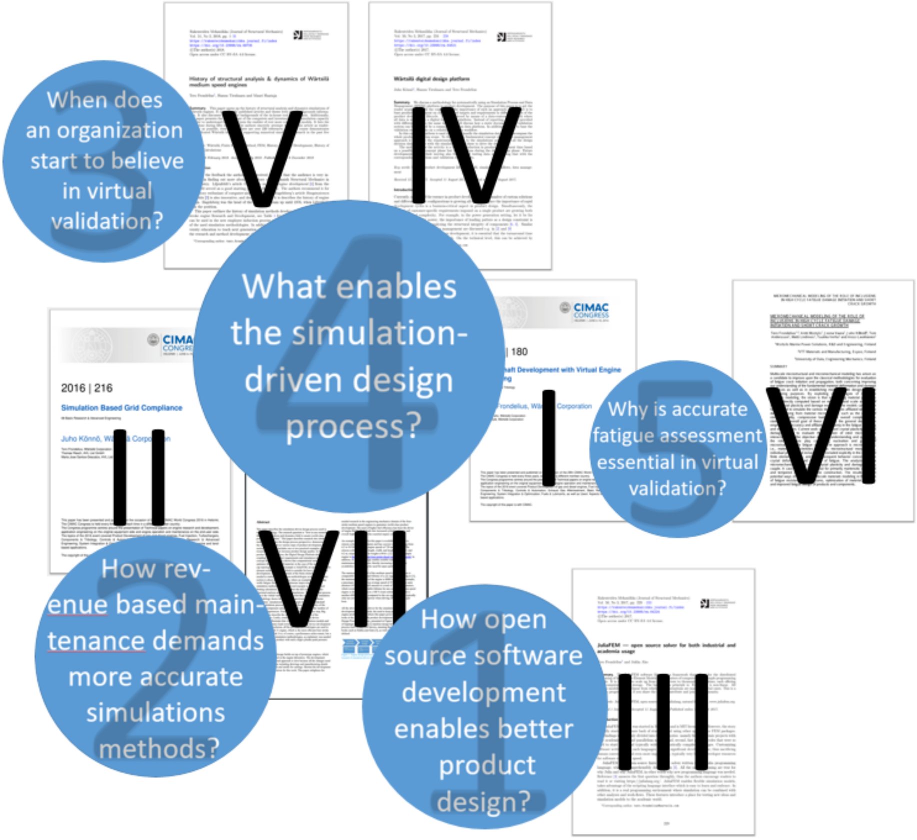

Fig. 2. Research questions and original research paper connections.

1.3 Research process and dissertation structure

This thesis builds on knowledge gained from the practical work experience during the past twelve years while working in the Wärtsilä R&D and Engineering organization. All of the results presented in this thesis are already published in the peer-reviewed articles.

All the method development exists because there has been a need for it. Naturally, it has not been possible to present every detail due to commercial interests. Also, in the next chapter 2, two different component calculation processes are taken as examples, namely these are crankshaft and cylinder head simulations processes, respectively.

1.4 Scientific novelty

The novelty in this thesis is the simulation-driven design process in engine development in practice. This thesis gives an insight into how the low-level simulation task connects to the high-level product requirement. Also, it explains how the world is changing towards open source tools and how those are beneficial for the industry. Next, best to the author knowledge, the scientific novelty of each original research paper is listed:

I This is the first paper describing the full complexity of the crankshaft fatigue dimensioning including field study of loading conditions, simulation of manufacturing effects, multiphysics virtual engine modeling, and advanced statistical fatigue analysis.

II This is the first paper for real crankshaft stress history in both short circuit and breaker opening cases. Our method couples the realistic engine control system to realistic virtual engine model in a unique way, which enables higher accuracy crankshaft simulation than earlier.

III This paper shows the benefits of new Finite Element solver. JuliaFEM enables flexible simulation models, takes advantage of the julia scripting language interface, and easily unites with other analyses and workflows.

IV This paper introduces the concept of requirements-based validation in the simulation process and data management (SPDM) environment. There customer's product requirement is mapped down to individual component simulation models.

V This is the first history article of fifty years in engine simulations. Also, it contains material from two interviews, which enabled much tacit knowledge from the past.

VI This is the first paper 'properly' capturing the effect to the fatigue of the interaction between inclusion in martensitic microstructure, and crystal plasticity-based micromechanics.

VII This paper highlights the research needed in the engineering mechanics domain of the four-stroke medium-speed engines to guarantee world-class product development.

2 Theoretical foundation

2.1 Simulation data and process management

In 2013, Brewster et al. [54] discus the whole engine development process and how simulations are a core part of it. However, already in 2004, Tussing [55] took a predictive-comparative analysis approach and showed that utilizing less simulation complexity but more consistency in simulation approach can enable the designer to affect product design with simulation positively. In 2016, Saito et al. [56], at new engine development of Niigata, has reasonably carried out simulation such as FEA (Finite Element Analysis) and CFD (Computational Fluid Dynamics) to achieve shorter development period, compact and lightweight engine design.

In 2016, Hynninen et al. [57] showed the easiness and usefulness of the automation of the dynamic simulation process of Genset application. They used an evolution algorithm in their optimization study. Naranca et al. [58], in 2016, demonstrated how important it is to have a single database based on which every simulation model is built. This way different departments and simulation experts will work on the same data, eventually contributing to the same project, ensuring that everyone is using the latest information during the product development project. However, already in 1984 Arar [59] published about a common base frame dynamic calculation. Moreover, a few years later in 1988 Rabb continued already with full models [60]. Also, the resilient mounting calculation was already developed in 1989, see Saine et al. [61].

In frequency domain full Genset model does not have enough accuracy for the crankshaft analysis. In the next chapter we will look into the needs of crankshaft virtual engine modelling.

2.2 Crankshaft calculations

Connecting rod calculations were the first ones to utilize multi-body dynamics system methodology in Wärtsilä operative calculations. Operative calculations here mean that the analysis in the new product development project should to be more accurate.

Crankshafts calculations leaped to the next level around the year 2010, when AVL Excite Power Unit was taken into use as Wärtsilä Virtual Engine Models (Figure 3). Before this time only the IACS M53 [63] crankshaft calculations were performed in practice, although Savolainen made his Master's thesis about this already at 2003 [14]. Dieghan et al. [64], in 2016, also noticed that it is crucial to combine mechanical and

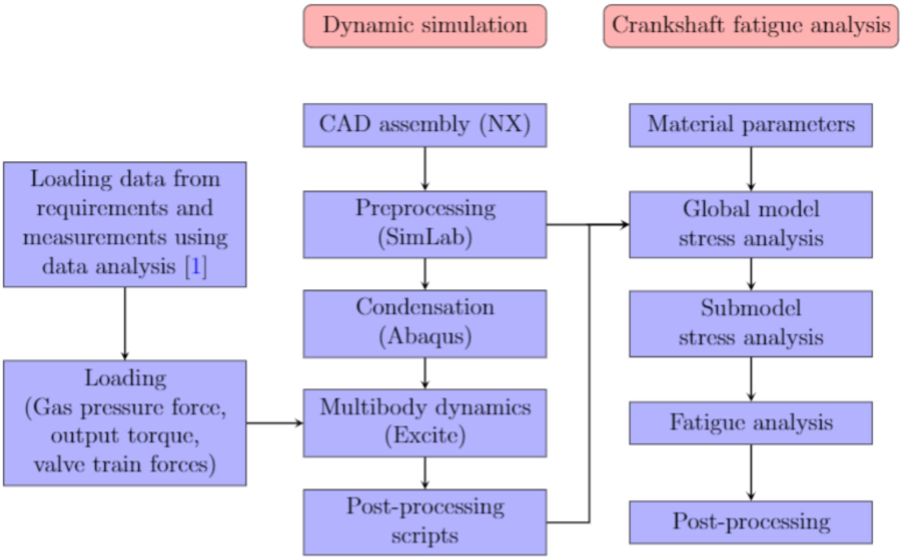

Fig. 3. Crankshaft analysis flowchart. Reprinted by permission [62].

performance firing order studies to find the global optimum firing order for the current cylinder configuration.

Of course, the main difference was not just to start using multibody simulation models. More importantly, different loading cases, including transient ones, were added to the simulation process. To name a few: emergency stopping, tripping and over speed were studied.

Crankshaft Deep rolling, see for example Hassani-Gangaraj et al. [65], is cold forming of the fillets of the crankshaft in order to get residual compression stresses, which will lead to higher fatigue limit. Therefore, the deep rolling is performed to increase the fatigue limit locally. Of course, this is smart because the highly loaded areas of the crankshaft are relatively small, see Figure 4.

Finding out the fatigue limit of the deep rolled crankshaft would mean the full-scale crankshaft fatigue testing. Thus, an alternative had to be found, and the deep rolling was simulated instead. The goal of the deep rolling simulation is to get the residual stresses of the crankshafts. Later, these residual stresses are used as a starting point of the crankshaft dynamics simulations.

Correct nonlinear material model is needed for both deep rolling simulation as well as crankshaft dynamics simulations, due to the fact that all loaded areas are already at the plasticity stress limit. Therefore, any additional load will make plastic deformations,

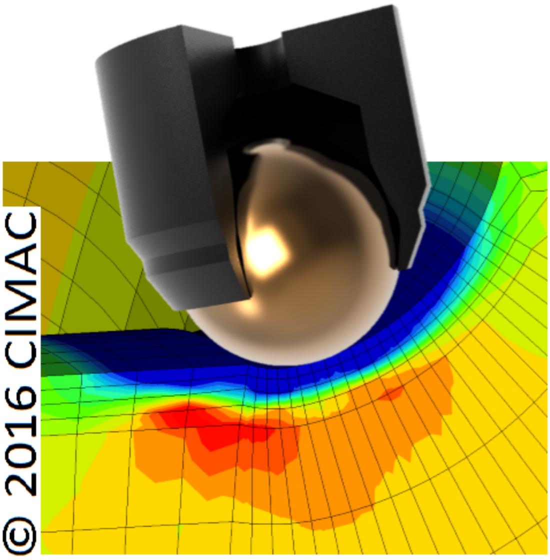

Fig. 4. Deep rolling of the crankshaft fillet. Distribution of the compressive (blue) and tension (red) stresses. Reprinted by permission [I].

which will mean that deep rolled crankshaft will find stable material state after first full loading conditions. This makes a critical requirement for the simulation that it needs to be performed in several engine cycles, just one is not enough, because of the plastic deformations and material hardening / softening.

Deep rolling simulation is relatively time-consuming. Thus, it is, at the moment, performed only for a sector model of the crankshaft. Then this sector results are cyclically copied for the whole fillet. Of course, this type of simplification will have a minor effect on the results, but these kinds of simplifications are needed in practice in order to get simulation results in a meaningful time. Talking about simulation times, in the next chapter we will look into cylinder head simulations, where computer performance always has been the bottle neck.

2.3 Cylinder head calculations

Cylinder head simulation methodology took a huge leap in a dedicated project called cylinder head task force. The project target was to get reliable cylinder head simulation results. Before this project, in the internal reports, wrong spots where indicated critical, and as a field experience we found cracking in different locations. Thus, the starting point was devastating because in reports we had so many low safety factors spots where cracks should initiate. Reflecting the experience, however, everything is fine, or even worse, and the cylinder heads fails from different locations.

Cylinder head task force was roughly a two years project with a budget of two million euros. It was successful cooperation between Structural Analysis & Dynamics, Thermofluids & Simulation, Materials and Cylinder Head & Valve train groups. Each of the dedicated simulations models use the same CAD model as a starting point, and this is the first time where such standardization could be achieved. In our PDM system, we made a dedicated simulation assembly, which is used for all three models meshing. The actual simulation steps and models are introduced in the following paragraphs.

Gas exchange simulations are the core of Thermofluids & Simulation group, and the purpose of this short introduction is not to dive into the details. Here the gas exchange simulations are presented in the boundary condition viewpoint only describing the coupling to the overall cylinder head calculation process.

Currently, this is the most time-consuming simulation in the workflow, especially for a gas engine, where one has a natural cycle to cycle variation in the burning. Gas exchange simulation needs boundary conditions from the full engine model, which is modeled in GT-Power in this case, after receiving the port pressures from the GT-model, then the simulation experts tune the gas exchange model to work in these boundary conditions. Then, the next step will be coupling this gas exchange model to the cooling simulation model, which is described next.

Conjugate heat transfer/cooling simulations are the other core competencies of the Thermofluids & Simulation group. Therefore, this model is also described briefly, and the focus is the delivery of the boundary conditions to the FEM model. In our case, this model is built in Siemens Star-CCM++ software, it contains all the components for one cylinder, see figure 5.

Conjugate heat transfer and gas exchange models are weakly coupled and looped until a certain convergence is reached. Like mentioned in the previous subsection: the gas exchange model simulation time is the bottleneck, especially when it is looped over and over again in order to reach the convergence of the two different models. Here a clear methodology development task remains open even after the cylinder head task force project was finalized. This development task is the responsibility of the manager of Thermofluids & Simulation. Hopefully, in the future, some performance improvement can be found.

The results of this model are the solid temperatures of the cylinder head simulations assembly. These will be mapped to the FEM model, which is Abaqus in our case. The mapping is done using the Star-CCM++.

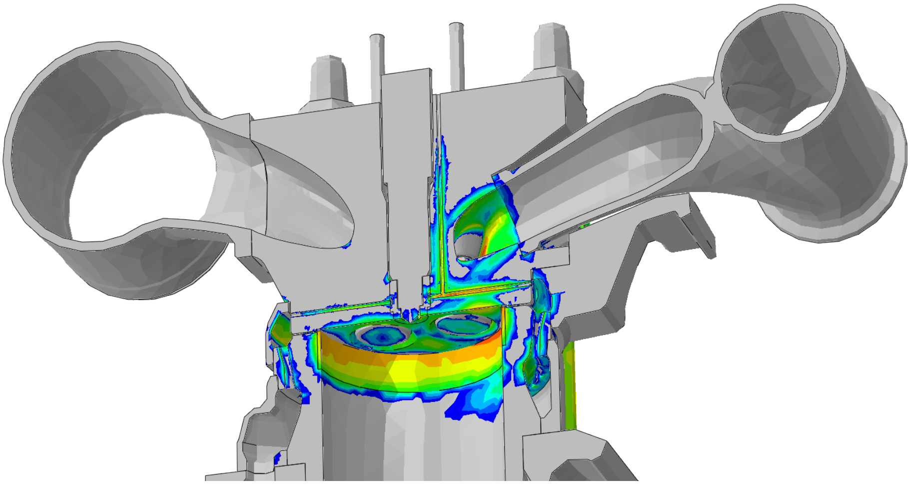

Fig. 5. Cylinder head fatigue lifetime. Reprinted by permission [66].

Casting simulation of the cylinder head is an extensive topic itself, but here only the FEM input data point of view is considered. Magma software is used to simulate the casting process. In the simulation model, the full process needs to be simulated, including the solidification process, in order to get the local material properties, which are needed input for the FEM simulation. Thus, the output of this model is the pearlite/ferrite 3D map interpolated to the FEM mesh nodal points.

The basic principle in casting simulation is the aim of robust design, meaning that the design is intolerant to the small changes which occur between different foundries. In other words, Wärtsilä's cylinder head design aims towards easy casting process in order to guarantee that all suppliers of Wärtsilä follow the same quality.

The significant improvement in the cylinder head calculation task was the inclusion of the CFD experts to the process flow. Although now the cylinder head calculation is much slower, it is also much more accurate than earlier. As a result, now it is easy to find the initiated cracks in the correct places and overall make much more accurate prediction of the weakest spots. More about this later. First, it is time to go through the FEM modeling.

Like already said earlier, the 3D CAD comes from dedicated simulation assembly, which is stored in our PDM system. The same CAD assembly is used for all simulations models in order to guarantee that the same version is simulated each time. Other input data is the materials library and casting simulations, details in the previous subsection. Material data is temperature, and pearlite-ferrite fraction depended.

FEM model itself is a state-of-the-art, starting from the modeling of the assembly loads, especially the challenging seat ring with multiple shrinks fits and contacts, continuing to the cyclic operation of the engine in order to find stabilized material state. Of course, it is impossible to run millions of nonlinear cycles, and we have to define methodologies in a way that few cycles will be enough for material stabilization.

Onera fatigue model is used to find the lifetime for cylinder head and liner. If the lifetime is lower than expected, it means crack initiation. However, damage tolerant design allows crack initiation, if we can show that the crack will not propagate. Therefore, a fracture mechanics approach is also needed. It will be the next topic.

Two level fracture mechanics are used. The first methodology is weight functions, where a pFAT program is used. The second one is the Zcrack, which is nonlinear fracture mechanics, actually modeling fracture into the FEM mesh and defining the contact surfaces between the crack faces. In 2013, Thumser et al. [67] showed how to use fracture mechanics in fuel injection component lifetime analysis. Also, Hertz et al. [68], already in 2006, used fracture mechanics in autofrettaged fuel injection components.

As described in this chapter, many commercial software needs to communicate with each other. Usually, it is inefficient and really complicated to set up co-simulations processes. In the next chapter, we will look into the open source software, which enables efficient scripting.

2.4 Open source finite element development

However, the story starts from years back of studying and using other open-source FEM packages. The findings divided into two categories: educational projects with academic goals and parallelism missing, and fast parallel codes really hard to use and typically written in statically compiled languages. Customizing software written using such languages requires significant developer time, thus sacrificing human convenience, and even more importantly, typically minimal developer resources for software execution speed.

Julia programming language enables a high level of abstraction in the programming code, such as using the automatic differentiation library ForwardDiff [69] for calculating gradients, jacobians, and hessians for all types of field data. Also, JuliaFEM is a real programming environment with full Julia language features enabling simulation combination with other analyses and workflows. In the next chapter we will see the benefits in practice.

3 Results

This chapter is divided into five sections to represent each five research questions of this thesis: 1) How open source software development enables better product design? 2) How revenue-based maintenance demands more accurate simulations methods? 3) When does an organization start to believe in virtual validation? 4) What enables the simulation-driven design process? 5) Why is accurate fatigue assessment essential in virtual validation?

3.1 Open source finite element development

The research question of this section is: How open source software development enables better product design? The main focus in this section is the JuliaFEM solver framework. The development started in May 2015, and the source code is MIT licensed [70]. The main advance of JuliaFEM is the development speed [III], which comes from the Julia language [71] dedicated to scientific computing.

Julia community provides a wide range of free software packages and a very educated online community eager to help and support the development work and especially optimize the software performance. JuliaFEM enables flexible simulation workflows, utilizes the easy to learn and embrace the julia scripting language interface. These features enable a framework for testing new ideas and simulation workflows to the academic research world.

Another significant feature of the open source software development is the possibility of building on top of existing open source projects. Thus, JuliaFEM offers an io-interface, to another open source FEM solver, CODE ASTER [72]. Developing both Julia and JuliaFEM encourages researchers to good practices including unit testing for, both, smaller and larger functions as well as to full integration testing of different platforms.

At the time of writing this thesis, JuliaFEM has the following analyze types available: elasticity, thermal, eigenvalue [73, 74], contact mechanics, and quasi-static solutions. For visualization, JuliaFEM uses Paraview [75] which prefers XDMF [76] file format using XML to store light data and HDF [77] to store large datasets, which is more or less the open source standard.

On the one hand, the vision of the JuliaFEM is MPI plus threading enabled massive parallelizations in cloud computing resources in Amazon, Azure [78] and Google cloud services together with a company's internal server [IV]. Moreover, on the other hand, for the real application complexity including the simulation model complexity as well as

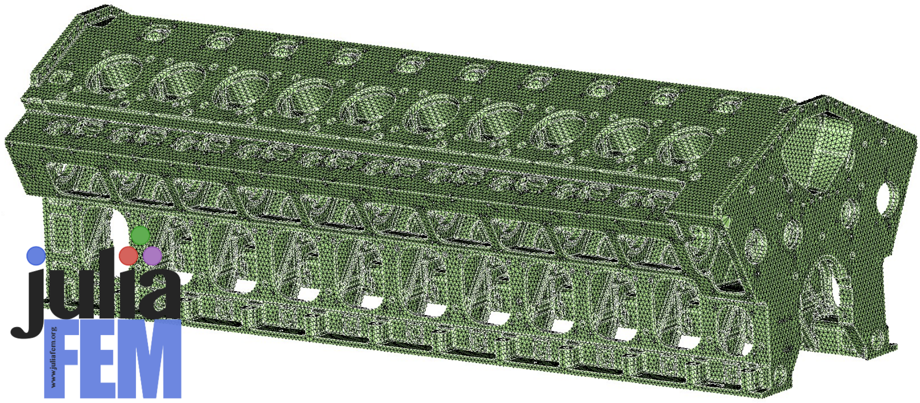

Fig. 6. JuliaFEM testing with a real industrial size FEM model. Reprinted by permission [III].

geometric complexity, see some examples in original papers [I, II] and [62]. Also, for the reuse of the existing material models, see [66].

Table 2. Table of the JuliaFEM solution times for an industrial size FEM models [III].

DOFS	Assembly time (s)	Solution time (s)	Total time (human readable)
3.0 M	458	312	16 min
10.8 M	3257	3255	2 h 4 min
12.6 M	3654	6318	3 h 4 min

Recreating the wheel again is nobody's goal, and thus the attempt is to use and embrace good practices and formats as much as possible. JuliaFEM implements Abaqus/Calculix [79] input-file format support. Modern environments for development enable fast development time and high productivity. For showing new ideas and making tutorials, we have used Jupyter notebooks [80] to make easy-to-use handouts.

The user interface for JuliaFEM is Jupyter Notebook [80], and Julia language itself is a real programming language. It makes it possible to use JuliaFEM as a part of a more critical solution cycle, including for example data mining, automatic geometry modifications, mesh generation, solution, and post-processing and enabling efficient optimization loops.

Typical examples in industrial applications include nonlinear solid mechanics [66], contact mechanics [81], finite strains [82], and fluid structure interaction problems. In the Figure 6 there is some simulation of machine parts having different amounts of elements and DOF's. For comparison, see Table 2. These simulations take a lot of computational resources, and here are the specs of the used hardware: 24 x Intel(R) Xeon(R) CPU E5-2690 v3 @ 2.60GHz with 512 GB total memory.

Open source tools are part of Wärtsilä's CAE democratization strategy as a way to save license costs. Simulation software licenses are typically expensive to acquire and maintain. Another attractive feature of the open source software in the CAE democratization sense is the source code availability. For example, the integration of open source FEM code to the automatic or semiautomatic simulation process in the Digital Design Platform or the designer's CAD software becomes easier, as can be seen in the next chapter.

3.2 Simulations methods to enable revenue-based maintenance

In field operation, often the electric grid imposes highly fluctuating loading conditions and anomalous phenomena on the generator. Examples of such phenomena are unstable grids with possible short circuits, heavily varying loading in peaking power plants or dredgers, or frequency fluctuations in small power grids. Typically, it is required to demonstrate the performance of the Genset by fulfilling certain grid compliance requirements, especially for unstable grids. Such tests are typically defined by legislation and target to assure that the generating set stays in the grid in the case of a transient event, for example, a short circuit or a breaker opening. One example is to show that the Genset stays in the grid during a short circuit of a few hundred milliseconds.

For the customer, this translates directly to the increased reliability in energy production through increased uptime of the power plant. On the other hand, running such heavy transients imposes elevated load levels on the engine and generator components. In order to guarantee that an engine will perform under all possible loading conditions during the engine lifetime, simulations are the viable choice to assure that such extreme loading does not affect the engine component lifetimes too much. Similarly, being able to simulate such events helps us to better understand and design the equipment for specific loading conditions and business demands of our customers.

The Wärtsilä 20V32 is 20-cylinder Genset which is used as an example in this study. The engine is a 55-degree V-angle 4-stroke diesel engine with a bore and stroke of 320 x 400 mm and rated speed of 720 or 750 rpm. It is an engine used in power plant installations, typically comprising several such Gensets. When installed to a small grid, such as on a standalone island application, the interplay of the Genset and the control system becomes one of the determining factors of the Genset performance. Consequently, understanding the coupled transient behavior is of utmost importance when designing Gensets for such demanding conditions.

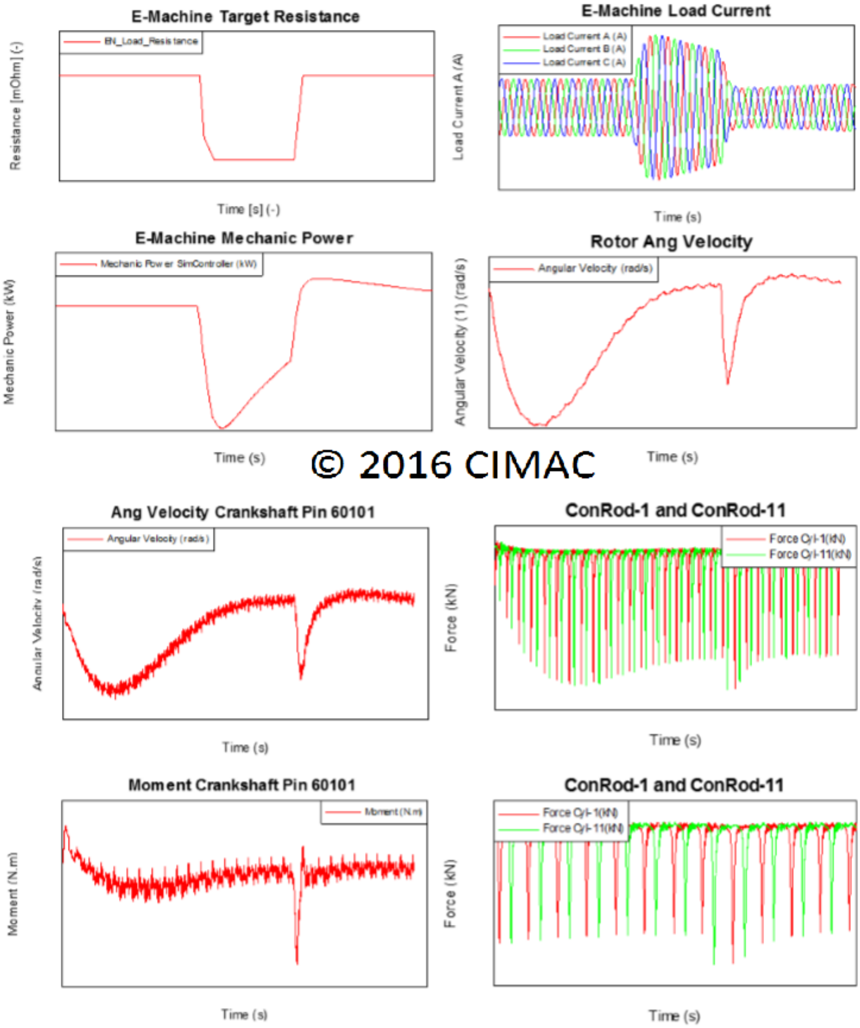

Fig. 7. Effect of the short circuit on the electric machine and the engine. Reprinted by permission [II].

Although traditionally grid compliance issues are related to power plant applications, one sees very similar challenges in marine applications as well. In a marine operating environment, the internal grid of the vessel is small, also leading to highly fluctuating loading conditions, in particular in specialized applications such as dredgers with highly varying power output demands. Ships, where there is both mechanical propulsion and electricity generation coupled to a single engine, are adding to the complexity. In such conditions, the Genset should be able to respond to the load changes rapidly enough and avoid destabilizing the electrical system of the vessel.

Besides, marine applications safety typically plays a key role. Also, to provide the most revenue through increased efficiency to the vessel operator, system simulation models help in assuring the safety on the sea of the equipment even under the most severe loading conditions.

The speed controller and the interactive online pressure load generation are tested through several validation cases with the model described above. A short circuit is a typical massive transient experienced by the generating set due to, e.g., trees falling on power lines or other network malfunctions. The motivation for presenting this specific application case is that it is very much connected to the component durability. Also, being able to simulate such transient events not only helps in assessing whether the component lifetime is reduced or not due to such an abnormal event, but it also allows the development of the automation and control system in such a way that the transient events are as gentle as possible on the engine and the whole generating set.

The test case consists of a steady state condition with an intermediate short-circuit for 100 ms which is modeled as a sudden decrease of the load resistance, as demonstrated in Figures 7. It also shows the change of the angular velocity of the rotor during a short circuit after an initialization period of three seconds for stabilization of the simulation model. In the short circuit event, the speed first decreases, then increases and finally starts to stabilize again. Mechanical power enters into a strong transient and then stabilizes. Voltages A/B/C of the three phases are also visible. The voltages are very sensitive to the applied resistance of short-circuiting.

Also, see the change of angular velocity at the end of the crankshaft during the short circuit. Similarly to the rotor shaft, after a period of initial stabilization, the speed first decreases, then increases and finally starts to stabilize. The transient reaction at the cylinder loads is visible. At first, the engine tries to reach the targeted speed by applying full load. It is the initial startup and stabilization phase. During the short circuit, the engine controller applies full load again due to the torque peak during the short circuit, trying to reach the maximum torque. All of the results agree qualitatively very well with the phenomena witnessed in measurements.

The exponentially growing amount of data creates the need to develop new methods for processing large data volumes automatically. Companies should see data analysis as important feedback: data acquisition from the field can be used in product development to make better products in the future. Collecting field data makes it possible to study and learn from the product in real-life conditions that are usually entirely different from the ones in a R&D laboratory. Thus, the data is essential for product development.

By collecting and examining data, a company can achieve remarkable competitive advantages over other companies in the same industry. If already delivered products start to malfunction, the only way to solve the problem and learn from it is to acquire measurement data from the field, do data analysis and provide options for problem solving based on the analysis results. The importance of data analysis is nowadays well understood [83], and companies have a rapidly growing need to find data analysts and software engineers or partners to improve the company data analysis capabilities. [I, IV], [84, 62]

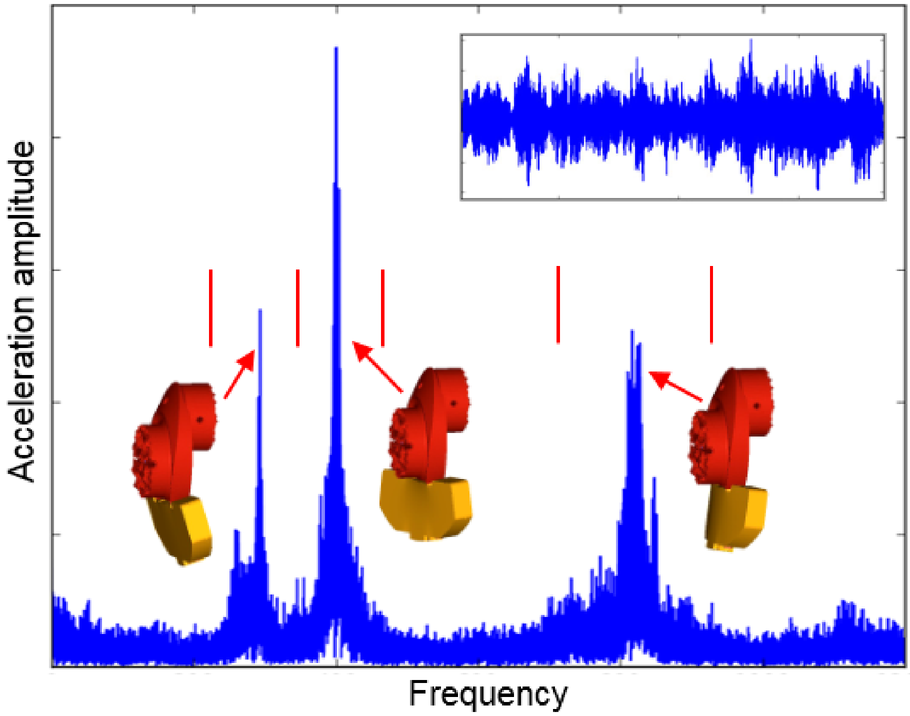

Fig. 8. Time signal and FFT spectrum of the measurement data. Reprinted by permission [84].

Companies have collected data themselves for a long time, but its systematic utilization in product design is often not done in the companies. Many times, the amount of data is a problem: it does not have to be very large for its analysis with, e.g., spreadsheet program to turn out to be impossible. It is also often the case that easy-to-use, ready-made programs for the specific needs of a company's data do not exist. The company may need to find partners or internal resources that are capable of delivering customized solutions for data analysis. Wärtsilä, together with suppliers, has years of experience in delivering a wide range of data analysis solutions, ranging from small desktop applications to the extended browser-based analysis services capable of analyzing hundreds of terabytes of data in computational clusters with thousands of calculation cores. [85]

The virtual model's verification depends on reliable data from the measurements. Usually, structural analysts together with measurement experts plan the subsequent measurements to get the maximum information from the measurements. However, much improvement in the statistical analysis of the measurement data is still needed. The potential to increase the accuracy of the simulation methodologies relies on big data analysis. One possibility for big data analysis is the embedded measurement data analysis.

The core feature of our developed measurement device is the original data post-processing inside the device. The purpose of the analysis is to get the displacement amplitudes of the counterweight for each specific eigenmode. Halla-aho et al. [84] have developed an intelligent algorithm that can perform all the needed calculations on the fly. The algorithm can be triggered automatically according to specified limit values to avoid unnecessary calculations when nothing unusual is happening. The mathematical principle of the algorithm builds on the Fast Fourier Transform (FFT) and double integration. The frequency bands for each selected eigenmode are defined remotely. The device performs the FFT of the acceleration signal and integrates it twice to displacement for each frequency band. Obtaining inverse FFT gives time signals of the displacement. Finally, a time window and the running amplitude principle are used to get the modal displacement amplitudes.

Figure 8 shows the time signal and FFT of the measurement data. The team validated the algorithm by comparing results from the device and analyzing traditional measurement data manually in the office. The calculation inside the box reduces the amount of data from a high-frequency time signal to a few essential numbers per second. Results are available in real time via a network. The manual effort of further data analysis is not needed but still possible. The algorithm can also be set to record raw data from unusual events if needed.

Like in the other case, the valid measurement data is the key for the verification of the virtual models. This device is planned to make long-lasting measurements inside a rotating engine. It uses a smart algorithm to store enough information for efficient data analysis. This way, the device saves energy and can keep measuring up for an extended period. From the measurements and model verification it is logical to move to the next chapter: when an organization starts to believe in virtual models.

3.3 When an organization starts to believe in virtual validation?

This section answers the research question: When an organization starts to believe virtual validation?

Pentti Rajamäki developed the first Wärtsilä internal Finite Element Method (FEM) solver in the year 1970 [86], by using the first edition of the Zienkiewich's book *The finite element method*, which was published 1967 and remained the only book about FEM until 1971 [87]. The FEM was taken into the production calculation usage quite quickly, as one can see from several documents. See details from the original paper [V].

Wärtsilä's Vaasa Factory acquired its first computer in the late 1970s. The intention was to use this HP1000 minicomputer for laboratory and production test bench measurements, as well as monitoring purposes on the test bench. The core size was 32 kilowords or 64 kb. Discs were not available; the structural analysts had to use the only mass storage device, which was a tape reader and punch device, used for both input and output. When Wärtsilä bought and installed a disc package with a capacity of a few 100 MBs in approximately 1980, the mesh size grew to at least 1000 degrees of freedom.

The very first commercial FEM usage was Harry Holmgren's Stardyne FEM course project work, where he calculated the Vaasa 32 main bearing cap [88]. It was also the first published Finite Element Analysis (FEA) [89], see the Figure 9.

Usually, behind all simulation tasks, there is a real need for the results. Another example of the common base frame dynamics simulation is Rabb's Master's thesis [60], which was initiated by a field vibrations problem of twelve delivered 18-cylinders V-engines of Vasa 32 type. These aggregates had enormous vibrations issues, and the customer was already at a point where the only outcome is the cancellation of the order, in other words, he was willing to return the nonworking aggregates to Vaasa. Rabb, together with his colleague Martikainen, did considerable work in calculating different field fix options. Finally, the solution was to add a bottom plate to the aggregates, which, of course at this point, was not a very attractive solution from the welder point of view. [90]

The work was only halfway when the technically feasible solution had been found to fix the problem. Next, someone needed to go and visit the angry customer and explain the somewhat technical problem. Liljenfeldt was assigned the job to go around the world and meet the customer. The customer was not convinced, and he wanted to bring his expert Ph.D. for the meeting the following day. The expert was not convinced with

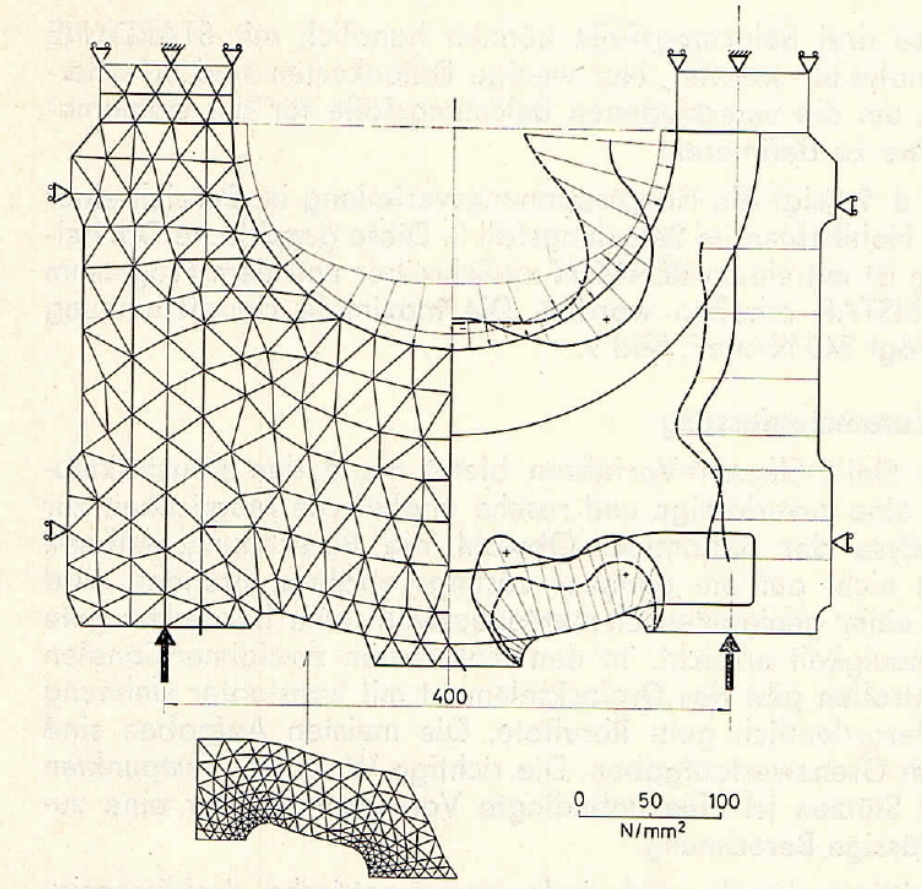

Fig. 9. Main Bearing Cap, FEM mesh and bending stress in some cut sections. Reprinted by permission from Springer MTZ – Motortechnische Zeitschrift [89], ©1976.

the idea of finite element computations and stood his ground about how it is possible to solve these sizes matrices by hand. Liljenfeldt tried his best to convince the expert about the fact that this is the solution, we trust our simulation model, and this change will fix the issue. At dinner, the customer gave partly in after revealing that their expert was a Ph.D. in history and promised Wärtsilä to try their best with one aggregate. However, he demanded that Liljenfeldt would stay and wait for these modifications to happen. Of course, this was not possible, it was Liljenfeldt's summer vacation, and he left back home to Finland. After the summer vacation, a letter was waiting from a genuinely angry customer who had already contacted Wärtsilä CEO about the poor customer assistance he had gotten from Liljenfeldt earlier. However, the story had a happy ending, as, after the modification, a comparison of a simulated and measured model showed that the correlation was excellent. It meant that the simulated model was quite exact compared to the measurements. Of course, this led to the situation where customer satisfaction was up again. The customer even ordered five more aggregates after the problem was solved [90].

Another way that Wärtsilä has been building customer trust in numerical computations is the active contribution in CIMAC Congresses. For example, in the year 1985 Ahlqvist et al. [91] presented a CAD-enabled design process, and in the year 1987 Paro et al. presented the effect of compression ratio to the durability of the crankshaft [92], which is the critical design question in engine concepts. Another interesting CIMAC contribution is the paper about the piston fatigue analysis from 1987 by Silvonen et al. [93]. On the topic of pistons reliability, Wärtsilä's supplier also published relevant results, see [94].

To succeed in simulation-driven development essentially means that the turnaround time for a single simulation is low enough. On the technical level, it can be achieved by simplifying the models used in the early design phase − often a non-trivial task in its right [95]. We aim to minimize this non-productive time spent by using a Digital Design Platform (DDP) system to simplify the validation and simultaneously assure the quality and reliability of the results.

The third essential ingredient is simulation democratization, meaning providing pre-configured simulation tools to non-expert users, which is a crucial selling point for many of the SPDM solutions nowadays and can be implemented in most of the solutions rather readily. However, the problem in the successful adoption of democratization depends more on the people involved: on the one hand, hard work on the simulation side to ensure robustness and functionality, and, on the user side, understanding the constraints of the pre-configured processes. To this end, we propose a workflow in which the analyst kicks off the activity. Then, for example, a parametric model is dealt by the designer or engine expert who takes over the work in running the design of experiments based on his expertise.

The most significant gain from a DDP solution, based on our current experience, can be gained by taking it a bit further by connecting it tightly to the requirements and the design workflow. It is also the grounds for a digital product since, without digital design data, it is challenging to build digital services around any product. As an example, we see a lifetime estimation of components not only as a validation step of the component but something we can offer as a tool to the customer to create added value to customer's business. Experience shows that this kind of a system requires changes in the thinking for those included in the product development process and also a bit of courage to let go of the well-established document-based way of working. One aspect is moving from a file-based procedure to a database system, based on author experience it takes time for the users to get accustomed to trust the database way of working with their data. On the other hand, digitizing processes and checklist for design assurance is sometimes met with opposition, partially due to the openness and transparency, partially due to the extra labor needed for the transition. The most critical lesson in the long proof of concept and deployment process has been that one should never consider implementing an SPDM tool as a software project, less about the software and more about adopting new ways of working.

As a conclusion, the main point to get an organization to believe into the virtual validation is the show cases, where important issue is solved with simulation, and the simulation accuracy is verified with measurements, and the gained knowledge is shared publicly for example in the Cimac Congress. In the next chapter, we will dive into the enablers of the simulation driven design process.

3.4 Enablers of simulation driven design process

This section answers the research question: What enables simulation-driven design process?

According to the original paper [I], safety and reliability are the cornerstones of the new product design. Besides, there has always been a request for higher engine efficiency, which can be achieved by increasing the peak cylinder pressure. For example in 2012, Ruschmeyer et al. [96] published that they increased peak pressures to be 250 bars.

Traditionally this has been an enormous challenge in engine design because the maximum bending force for the crankshaft comes from the peak pressure. Virtual Engine modeling has helped to overcome these challenges.

Guinness World Record 2015: The most efficient 4-stroke engine ever is strongly based on a high peak cylinder pressure [97]. The highest design cylinder pressure ever for the medium speed engines has been a real driver towards Virtual Engine modeling. Also, the increased demands on grid compliance [98] and the increasing complexity of the ship hybrid thrust systems have been important contributing factors as well.

Engine fast loading capability has increased its importance among customers. It created the need for accurate transient simulations, a realistic virtual engine model, which enables modeling of any power plant grid transients, such as short circuits and breaker openings [II], but also full propulsion system operation. As an example, the electric grid can be a modern ship hybrid mechatronic operation, a small power plant in island mode with heavy mining machinery, or offshore drilling platform operation.

According to the original paper [II], to accurately simulate transients, one cannot merely use static parameters, e.g., for the output torque and cylinder pressure. Examples of such transient simulations are studies on, e.g., whether the Genset will survive a short circuit or not without falling off the grid. To accurately simulate such events, one needs to consider the mechanical model of an engine as a model coupling with corresponding automation and electrical models. Consequently, this coupled model will serve the needs of not only mechanical simulations, but it also acts as a testbed for control system development in a virtual environment. Therefore, delivering better solutions to the customer in a shorter amount of time. In the daily operation of a Genset in a power plant or marine installation, such high transient effects play an essential role and demand to consider it in the development of the engine control system.

In field operation, Gensets are often subject to fluctuating loading conditions and phenomena imposed on the Genset by the electric grid. Such events are unstable grids with short circuits, massively varying loading in power plants, or frequency fluctuations in small power grids for example. Typically, it is required to demonstrate the performance of the Genset for unstable grids by fulfilling specific grid compliance requirements.

Typically, legislation dictates such tests and aims to assure that the Gensets stays connected to the electric grid in the case of a transient event, such as a short circuit or not planned breaker opening in the grid. A typical demo case is to show that the Genset stays in the grid during a short circuit of a few hundred milliseconds.

Although grid compliance issues are related to power plant applications, one faces very similar challenges in marine applications as well. In a marine operating environment, the internal grid of the vessel is small, also leading to highly fluctuating loading conditions, in particular in individual applications with varying power output demands, such as dredgers and oil rigs. Adding to the complexity of the case, customers also have installations where there is both mechanical propulsion and electricity generator coupled to a single main engine. In such conditions, the Gensets should be able to respond to the load changes rapidly enough and avoid destabilizing the electrical system of the vessel.

Besides, in marine applications safety typically plays a key role. In addition to providing the best economic output through increased efficiency to the vessel operation, tightly coupled mechanical and full system simulation models help in assuring the safety on the sea of the equipment even under the most severe loading conditions.

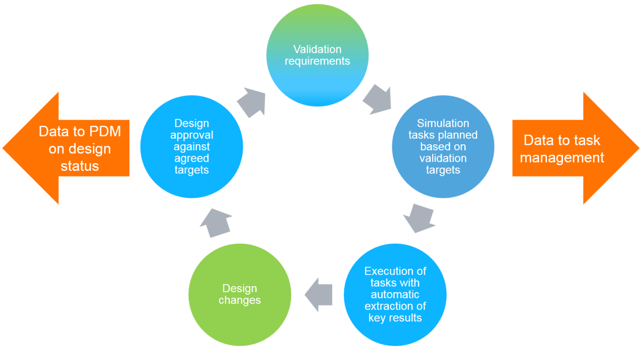

Fig. 10. Basic data flow in the requirements-based validation SPDM system- Reprinted by permission [IV].

According to the original paper [IV], to succeed in simulation-driven development, it is a must that the throughput time for a single simulation is low enough. On the technical level, organization achieves this by simplifying the models used in the early design phase – often a non-trivial task in its own right [95]. We aim to minimize this waste time by using an SPDM system to simplify the validation workflow and at the same time assure the quality and reliability of the results. The data flow in planning and running the validation workflow for specific product development is presented in Figure 10, which illustrates the complete validation and design process loop from requirements to design and the corresponding data flow presented by the arrows. The green activities are in the Product Data Management (PDM) system, while the blue activities happen in the SPDM system, with orange arrows presenting the flow of data both the task management and to the PDM system for saving design data.

The existence of a single enterprise-wide solution platform is quite rare. In reality, the software landscape consists of several tools from different vendors, linked with different levels of automation, usually by point-to-point integrations. Typically, this leads to inefficiencies in the dataflow between different departments and design teams. Quite often critical data is lost somewhere along the way which directly translates to costly delays in new product introduction. As pointed out by [99], one of the critical elements for a successful Product Lifecycle Management (PLM), and thus also an SPDM system, is the cohesion between all different product views, let it be mechanical design, automation, electrical or bill of materials, to name a few. In the validation set, this translates to the vital concept of knowing what should be validated and, most importantly, how. Only then one should go to planning, not happily skipping those above two critical steps.

In conclusion, the most significant gain from an SPDM solution, based on the experience, can be gained by taking the system a bit further by connecting it tightly to the requirements and the design workflow. It is also the foundation for a digitally enabled product since, without digital design data, it is impossible to build digital services around any product. As an example, we see lifetime estimation not only as a validation step but something we can offer as a tool to the customer for creating added value. Wärtsilä has also found out that this kind of a system requires changes in the mindset for those involved in the product development process and also a bit of courage to let go of the well-established document-based way of working. One aspect is moving from a file-based approach to a database system. Based on our experience it takes time for the users to get accustomed to trust the database solution with their data. On the other hand, digitizing processes and checklist for component assurance is sometimes met with resistance, partly due to the openness and transparency, partly due to the extra effort needed for the transition. The most critical lesson in the long proof of concept and deployment process has been that one should never consider implementing an SPDM tool merely as a software project, less about the software and more about embracing new ways of working.

According to the original paper [V], usually, behind all simulation tasks, there is a real need for the results. Repeating the example from the previous chapter: the case of the common-base-frame dynamics simulations is Rabb's Master's thesis [60], which was initiated by a field vibrations problem of twelve delivered 18-cylinders V-engines of Vasa 32 type. These aggregates had enormous vibrations issues, and the customer was already at a point where the only outcome is the cancellation of the order, in other words, he was willing to return the nonworking aggregates to Vaasa. Rabb, together with his colleague Martikainen, did considerable work in calculating different field fix options. Finally, they discovered that the solutions was to add a bottom plate to the aggregates, which of course at this point was not a very attractive solution from the welder point of view. [90]

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Ph.D. in history, and promised Wärtsilä to try their best with one aggregate. However, he demanded that Liljenfeldt would stay and wait for these modifications to happen. Of course, this was not possible, it was Liljenfeldt's summer vacation, and he left back home to Finland. After the summer vacation, a letter was waiting from a genuinely angry customer who had already contacted Wärtsilä CEO about the poor customer assistance he had gotten from Liljenfeldt earlier. However, this story had a happy ending, as, after the modification, a comparison of a simulated and measured model showed a strong correlation. It meant that the simulated model was quite exact compared to the measurements. Of course, this led to the situation where customer satisfaction was up again. The customer even ordered five more aggregates after the problem was solved. [90]

Another way that Wärtsilä has been building customer trust in numerical computations is the active contribution in CIMAC Congresses. For example, in the year 1985 Ahlqvist et al. [91] presented a CAD-enabled design process, and in the year 1987 Paro et al. presented the effect of compression ratio to the durability of the crankshaft [92], which is the crucial design question in engine concepts. Another interesting CIMAC contribution is the paper about the piston fatigue analysis from 1987 by Silvonen et al. [93]. On the topic of pistons reliability, Wärtsilä's supplier also published relevant results, see [94].

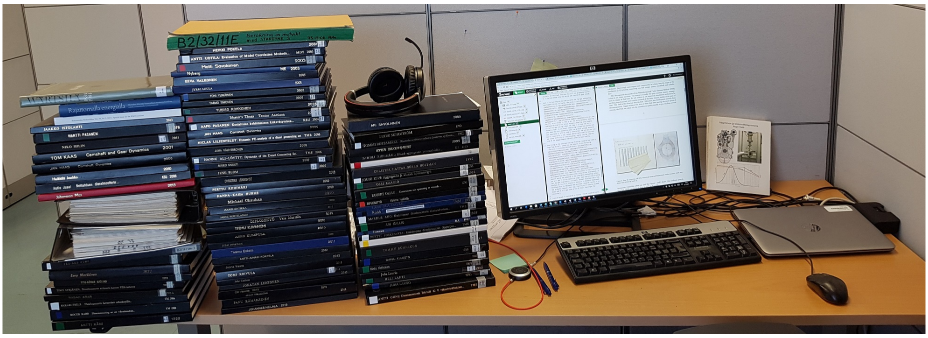

Fig. 11. Authors's desk when going through the references. Reprinted by permission [V].

Figure 11 shows a part of the overwhelming task of going through all the references. Although it took a considerable amount of effort, the authors believe it was worthy for gaining a better understanding of what we have done and where we should be heading. It also revealed the somewhat surprising fact that Wärtsilä has not published much about optimization development as such. Our competitors and other industry have been more active for example Boehm et al. [100] in 2010 showed different components topology optimizations or Keski-Rahkonen a product optimization [101] in 2017.

Structural analysts have mentioned optimization in some articles as a side note, but we have, indeed, not published as much as we have used it internally.

According to the original paper [VII], traditional engine design builds on top of prototype engines and their testing in the engine laboratory. The development cycle of the traditional approach is slow because all the changes need to have a detailed design including drawings and manufacturing details like CAM programs and molds for castings. Shortening the development time was the motivation for this work. The paper enlightens the needed research in the engineering mechanics domain of the four-stroke medium speed engines to guarantee world-class product development. The need for higher fuel efficiency has been the driver of engine R&D which leads into increased cylinder pressure and overall higher stresses in the essential engine components.

All the above has been a driver for the simulation method development, in other words, the need to keep producing the reliable engine products. That is where this thesis gives the big picture and looks at the topic from the product development process perspective. Design Process of Engines, presented in Figure 1, follows the process of Eppinger and Ulrich's [2] machine design book quite strictly. The process itself is very well-known, meaning that all machine design books, such as Hubka and Eder [3], as well as Ullman [4], have it defined.

As a conclusion, the first enabler is that the organization believes in the virtual validation. Secondly, the safety and reliability of modern era products with complex product requirements is achieved by enormous simulation case matrix, where for example Genset's transient loadings are taken into account. Finally, a working SPDM system is a must, where simulations tasks can be performed efficiently. In the next chapter, we will look a major contributor to the product reliability, namely fatigue assessment.

3.5 Fatigue assessment in virtual validation

This section answers the research question: Why accurate fatigue assessment is essential in virtual validation?

Multiscale microstructural and micromechanical modeling has arisen as a candidate to improve the classical methodologies for evaluation of fatigue crack initiation and propagation, both concerning improving our understanding of the fundamental material deformation and damage processes as well as in establishing more accurate design rules for engineering purposes. By exploiting methodologies of multiscale materials modeling, the vision is that engineering material properties can be directly computed based on microstructural scale analysis of single crystal plasticity and damage evolution.

The models can then be further used to simulate the various dependencies affiliated with fatigue damage arising from material microstructure, such as the effects of stress triaxiality, compressive loading, and overall complex stress states. The overall goal of these efforts is the general decrease in empiricism, inaccuracy and affiliated uncertainty in the fatigue modeling and design chain. Current work utilizes novel crystal plasticity coupled damage model to evaluate the inclusion of steel microstructure interactions with the objective of better understanding and quantifying the role inclusions play in nucleation and growth of microstructure scale fatigue cracks. The approach is microstructural, i.e., material characteristics such as microstructural morphologies, individual phases, and inclusions are included explicitly in the numerical finite element models, and the subsequent behavior concerns single crystal deformation and initiation of fatigue. The analysis uses a micromechanical model where crystal plasticity and damage directly couple. A case study is carried out for primarily martensitic quenched and tempered steel for machine construction. The results suggest potential ways of exploiting multiscale materials modeling in the design of fatigue resistant microstructures, optimization of material solutions, and improved fatigue design of products and components.

This section describes the methodology of micromechanical modeling [102] of the high cycle fatigue test bars [103]. The researchers prepared representative microstructural models of a quenched and tempered steel containing a non-metallic inclusion, and the deformation and damage response under cyclic loading was solved utilizing crystal plasticity based micromechanical damage models. High cycle fatigue and the deleterious role inclusions play in the fatigue limit of a fatigue crack is summarized in [104]. High cycle fatigue rules the dimensioning of medium speed crankshafts [62], [I]. Another high cycle fatigue related phenomenon is fretting fatigue [105, 106], which is one of the main dimensioning features of connecting rod [107]. Another, maybe more complex, related phenomenon is thermomechanical fatigue [66, 108].

In the current work, a micromechanical model where crystal plasticity and damage directly couple is employed in the analysis of fatigue along with fatigue performance indicators. As such, the appearance of material damage during cyclic loading at microstructural cleavage planes can be observed based on a single crystal slip, as well as interactions arising from the stress-strain states of the inclusion and the metallic microstructure. A case study is carried out for primarily martensitic quenched and tempered steel for machine construction. The study addresses the role of inclusion properties and its size relative to the martensitic microstructure. The results suggest potential ways of exploiting multiscale materials modeling in the design of fatigue resistant microstructures, optimization of material solutions and improved fatigue design of products and components. Next, we will look the boundary conditions for microscale model which comes from the virtual engine model.

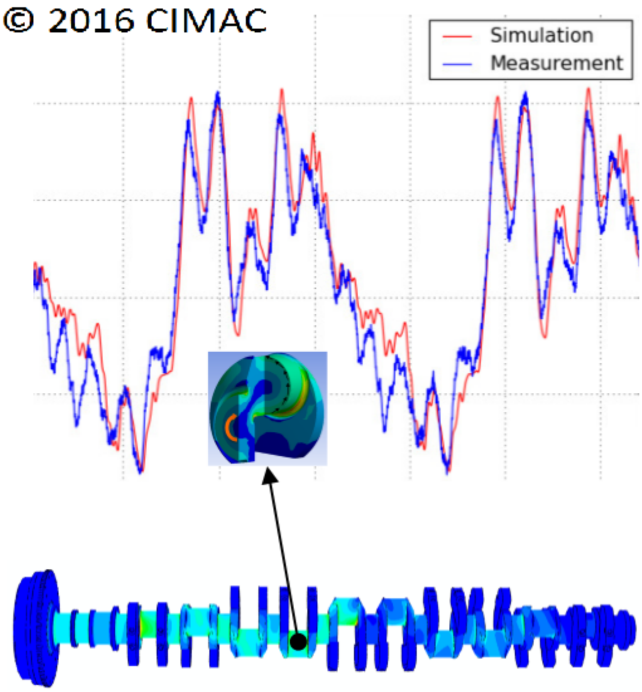

Fig. 12. Simulated and measured torque of the crankshaft in the midpoint of the shaft. Reprinted by permission [I].

The bearing and gear models of a multibody system are based on real physical parameters, like clearances and oil supplies to the bearings, and they are therefore very well defined, minimizing the number of assumptions needed in comparison to more simple methods. Of course, complex models require proper verification through measurements which shows that Wärtsilä Virtual Engine approach can be very accurate for the powertrain dynamics even up to very high frequencies, like counterweight vibrations. Figure 12 illustrates torsional vibrations of a long shaft in a time domain. The simulated curve follows amazingly well the measured one. Primarily, it shows that the model captures all the dynamic crankshaft phenomena.

The dynamic boundary conditions from the Wärtsilä Virtual Engine models can be used in component level simulations to apply realistic boundary conditions for stress analyses, which are essential for accurate fatigue analysis.

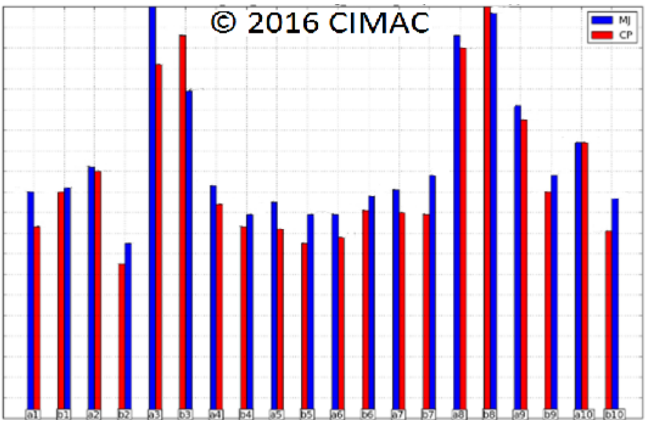

Fig. 13. Simulated safety factors along the crankshaft. Blue bars are Main Journal (MJ) and red bars are Crank Pin (CP) fillet safety factors. Reprinted by permission [I].

Due to the complicated loading, statistical and multiaxial fatigue analyses are required to ensure reliable crankshaft design. Equation (1), see [109], describes the interference failure probability:

$$P = \int_{-\infty}^{\infty} f_s(\sigma_s) \int_{-\infty}^{\sigma_s} f_f(\sigma_{af}) \mathrm{d}\sigma_{af} \mathrm{d}\sigma_s, \tag{1}$$

where P is maximum allowed probability of failure considering the randomness in both stress and strength, $f_s(\sigma_s)$ is density function for the stress σ_s, and $f_f(\sigma_{af})$ is density function for the fatigue limit σ_{af}.

With this approach, the stresses in every detail in the shaft are calculated using the finite element models driven by the loadings from the Wärtsilä Virtual Engine. In Figure 13, the uneven distribution of the crankshaft safety factors is shown as an example. It is the clear benefit compared to the current IACS UR M53 rules. Manufacturing effects, such as grain flow and residual stresses from, e.g., deep rolling, are considered in the finite element analysis as they have a significant impact on the fatigue strength of the crankshaft. Furthermore, fracture mechanics with the short crack approach is used to consider the effects of material inclusions on fatigue safety. The model includes transient loads from the grid or propulsion systems. Finally, all of these phenomena are statistical. Therefore, Structural Analyst has to consider deviations of the loading and material parameters which is done through extensive measurements and testing on engines in real life operation at customers.

As a conclusion, a single component fatigue life dimensions the whole product lifetime. The more accurate one can simulate the component lifetime expectancy the more cost efficiently the component can be manufactured thus lowering the product cost.

4 Discussion

4.1 Theoretical implications

The Digital Design Platform (DDP) creates the basis for simulation driven design process. Research shows that DDP increases internal communications and reduces the old data mistakes when everyone is accessing the life data in the database. It also guarantees that everyone has access to all product data. The way that customer requirements are connected all the way through to simulation results ensures that if someone has changed them or someone needs to change them, project management understands the whole needed effort and the interconnectivity of the individual requirements and design tasks with its validation. When FMEAs connect the simulation tasks and requirements we are in a central position of simulation-driven-design management.

In the concept design and concept simulation section of the original research paper [VII], the two examples were main bearing cap topology optimization and JuliaFEM platform, respectively. All numerics have come here to stay, and, as already mentioned, in the future topology optimization toolboxes will have more and more intelligence, and they will be more independent automatic design creation tools. The other example, the JuliaFEM platform, goes deep into the academic world. There is a need for a full-featured FEM code in the modern scripting language environment because the users with industrial size models want to benefit from open source platform development where one writes the missing piece of code.

The Detailed design section of the original research paper [VII] presents two examples, fatigue simulation of oil sump welds and connecting rod fatigue and fretting calculations, respectively. Optimization of the welds' details, although manual optimization, in this case, is needed for reliable oil sump design. The Devil is in the details, and, thus, a small modification in geometry leads to a considerable increase in life expectancy. The connecting rod simulation showed significant correlation to the dynamic measurement with the average difference only 0.8%. Also, the importance of basic research on fretting fatigue was highlighted. Without understanding the fundaments of fretting fatigue, it is nearly impossible to design reliable medium speed connecting rods.

Also in the Virtual Validation section of the original research paper [VII], two examples are shown, namely cylinder head and crankshaft simulation processes. These are the high-end simulation cases, where a lot of method development and research were needed to polish the processes in these conditions. The crankshaft case shows a sound correlation to the verification measurements. Both processes are the backbone of the Structural Analysis and Dynamics team's work.

Finally, the Validation and product testing section end the original research paper [VII] with two examples: big data analysis and counterweight fretting measurements. Both of these emphasize how vital close co-operation between virtual validation and validation teams is. Deploying virtual engine models, an analyst can design the best possible measurement points to make the model verification as easy and as accurate as possible.

Overall, this thesis explains the importance of the engineering mechanics research for the company, whose aim is to maintain the technology leadership position. This thesis deals with the different product development project phases in light of real-life examples. These examples offer excellent building ground for the rest of the industry to follow, catch, and try to overtake.

4.2 Practical implications

The results presented in this thesis are precious to Wärtsilä, who has been the early adopter of the simulation-driven design process, as explained in the original paper [VII]. To be more concrete, let us see it through examples.

Crankshaft simulation methodology has gone through a significant overhaul from simple IACS MathCAD calculations to state-of-the-art virtual engine modeling, as explained in [V]. The methodology starts from including manufacturing effects, real loading conditions from the field, and statistical fatigue methodology, like the original paper [I] shows. Besides, including extreme loading cases correctly, like short circuits and breaker openings, is crucial for getting the crankshaft field loading conditions taken into count when designing it, as discussed in the original paper [II].

Wärtsilä has long had a leading position in the fatigue methodology development as discussed in the original paper [V]. To take it to the next level, using the micro-mechanics for describing the interaction between the nonmetallic inclusion and the martensitic microstructure, is shown in the original paper [VI]. All this cutting edge research benefits from open source finite element solver, which is fast to develop and yet still high performance enough for industrial size model solving, as explained in the original paper [III].

In Wärtsilä's engine development projects, the new presented methodology is in use. Wärtsilä 31 product was the first using the new methodology, and the results speak for itself, it is the most efficient 4-stroke engine in the world.

Rest of the Finnish industry will benefit from the results as well. All of these new findings will eventually merge into the machine design teaching in the University of Oulu. Thus, the next generation designers will have the new set of tools when they enter the job market.

4.3 Reliability and validity

This thesis content is valid for all industry. Currently, it is only tested in the engine development environment. However, simulation-driven design process, as described here, is an abstract approach which other kinds of businesses who develop and produce concrete products can quickly adapt to.

Reliability of this kind of general methodology is hard to measure, but all results presented here have earlier gone through a peer review process, and reliable publishers published the results.

4.4 Recommendations for further research

Even though the simulation-driven design process has been a very much needed change in the mindset, it is just the beginning of the work. The introduced methodology still focuses each technical design item individually, and the big picture of the full design remains tacit knowledge in the project and design managers heads.

Therefore, the further research should move towards model-based engineering – full system-level models, which will define the full system, for example a full ship. These components in the models define input and outputs and, thus, make the interfaces between components visible. Also, the system should be run in continuous integration environment, same way as software engineers are all the time testing the code base during the development.

Also, it is a one thing to do research and develop new methodologies and other to get all new methods implemented in the production. Luckily, Wärtsilä is building a smart technology hub in Vaasa Vaskiluoto, which gives a great opportunity to switch to a better way of working at the same time. The idea behind the hub is to make collaboration between universities, small companies, and industry as smooth as possible. The hub ensures future research and development staff high targeted education, where this thesis work can be utilized as well.

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Original publications

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II Könnö J, Frondelius T, Resch T & Santos-Descalzo MJ (2016) Simulation based grid compliance. In: CIMAC Congress Helsinki.

III Frondelius T & Aho J (2017) JuliaFEM —open source solver for both industrial and academia usage. Rakenteiden Mekaniikka 50(3): 229–233. `https://doi.org/10.23998/rm.64224`. Open access.

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VI Frondelius T, Mäntylä A, Vaara J, Könnö J, Andersson T, Lindroos M, Verho T & Laukkanen A (2018) Micromechanical modeling of the role of inclusions in high cycle fatigue damage initiation and short crack growth. In: CAASE18 The Conference on Advancing Analysis & Simulation in Engineering. Nafems.

VII Frondelius T, Tienhaara H, Kömi J & Haataja M (2018) Simulation-driven development of combustion engines: theory and examples. SAE Technical Papers. ISSN: 0148-7191 `https://doi.org/10.4271/2018-01-5050`. Open access.

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