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PRODUCT DEVELOPMENT OF A TRACTOR BASED ON EXTENSIVE USE OF SIMULATION TOOLS

Examiner(s): D. Sc. Aki Mikkola

D. Sc. Kimmo Kerkkänen

ABSTRACT

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Product development of a tractor based on extensive use of simulation tools

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The majority of manufacturing companies are increasingly focused to decreasing product development time, costs, and introduction time to market. As a result of virtual simulation implementation to product engineering, SDPD (Simulation Driven Product Development) has been introduced as a method to further improve the efficiency and quality of product development.

This study focuses on finding simulation solutions to decrease time and cost of prototyping, and introducing SDPD to tractor research and development with the help of simulation process guiding maps. By investigating literature and research of different simulation methods, the reduction of the high amount of prototype manufacturing and physical testing present in R&D (Research and Development) departments are highlighted. The DVP (Design Verification Plan) tests of a tractor NPI project are suggested to be partially replaced by different simulation methods, but only through extensive further studies of each system or module of a tractor. Trust for simulation results, with further experience and knowledge in both physical and virtual testing is identified as a precondition for increasing simulation in DVP tests.

The increased potential of SDPD is already noticed by simulation performing engineers. The need for simulation support from PDM systems in R&D departments can furthermore reduce barriers created by different areas of expertise, increasing cross functional co-operation. Being also a major discovery of this study, simulation further improves the understanding of design properties of different parts and modules that are used and developed by the design engineers. It seems to be not only a resource efficient way of decreasing PD process lead-time, but it can also decrease the learning time of engineering.

TIIVISTELMÄ

LUT-Yliopisto

LUT School of Energy Systems

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Simulointityökalujen laajamittainen hyödyntäminen traktorin tuotekehityksessä

Diplomi-insinöörityö

2019

75 sivua, 22 kuviota ja 11 liitettä

Tarkastajat: D. Sc. Aki Mikkola

D. Sc. Kimmo Kerkkänen

Hakusanat: simulointi, tuotekehitys, riskienhallinta, prototyyppi, traktori

Valtaosa valmistavan teollisuuden yrityksistä keskittyy yhä enenevässä määrin tuotekehitysajan, kustannusten ja tuotteen markkinoille saattamisajan vähentämiseen. Virtuaalinen simulointi on tuotu tuotesuunnittelun osaksi SDPD:n (Simulation Driven Product Development) avulla, joka on otettu käyttöön yhtenä tuotekehityksen tehokkuuden ja laadun parantamisen menetelmänä.

Tässä tutkimuksessa keskitytään prototyyppikeskeisen traktorin tuotekehityksen ajan ja kustannusten supistamiseen simuloinnin avulla, sekä SDPD:n käyttöönottoon ohjeellisten prosessikarttojen avulla. Tutkimalla kirjallisuutta ja olemassaolevaa tutkimustietoa virtuaalisesta simuloinnista, työssä korostetaan ekstensiivisen prototyyppivalmistuksen ja fyysisen testauksen supistamista tuotekehityksessä. Traktorin DVP (Design Verification Plan) testien sisältöä ehdotetaan korvattavaksi osittain simulointimenetelmillä, mutta vain tarkkojen lisätutkimusten ja tulosten vertailun avulla. Luottamusta simulointituloksiin tulee lisätä virtuaalisen ja fyysisen testauksen lisätiedon ja kokemuksen kartuttamisen kautta, joka tunnistetaan edellytyksenä lisätä simulointia DVP testeissä.

SDPD:n lisääntynyt potentiaali on jo havaittu simulointia suorittavien insinöörien keskuudessa. Simulointituen tarve PDM järjestelmiltä tuotekehityksessä voi lisäksi vähentää eri osaamisalueiden luomia muureja, mikä lisää rajat ylittävää yhteistyötä. Tutkimuksessa merkittävä huomio on myös se, että simulointi parantaa entisestään suunnittelijan käyttämien suunnittelukomponenttien ja -moduulien ominaisuuksien ymmärryksen tasoa. Se ei ole pelkästään resurssitehokas tapa vähentää tuotekehitysprojektin läpimenoaikaa, vaan se voi myös vähentää suunnittelun ohessa oppimiseen kuluvaa aikaa.

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Jaakko Noronen

Jaakko Noronen

Jyväskylä, Finland, June 2019

"All models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind."

George E. P. Box

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Appendix VIII: Field issues and warranty statistics, which could not be prevented through simulation during the project

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LIST OF ABBREVIATIONS

CAD	Computer Aided Design
CAE	Computer-Aided Engineering
CFD	Computational Fluid Dynamics
DFMEA	Design Failure Mode and Effects Analysis
DVP	Design Validation Plan
EAT	Exhaust After Treatment
FEA	Finite Element Analysis
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
FVM	Finite Volume Method
HVAC	Heating, Ventilation, and Air Conditioning
LAT	Limiting Ambient Temperature
M&S	Modelling and Simulation
MBS	Multibody System
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NPI	New Product Introduction
NVH	Noise Vibration Harshness
PD	Product Development
PDM	Product Data Management
PLM	Product Lifecycle Management
PTO	Power Take Out
R&AE	Research and Advanced Engineering
R&D	Research and Development
ROPS	Rollover Protection Structure
RPN	Risk Priority Number
SDD	Simulation Driven Design
SDM	Simulation Data Management
SDPD	Simulation Driven Product Development
SLM	Simulation Life-cycle Management
VE	Virtual Environment

1 INTRODUCTION

Tractors have been human aids in food production since the first steam-powered equipment from the mid-19th century, and have been under continuous development to this day. There have been different stages of innovation in every aspect of the tractor; with engine, cab, power transmission, and more modern electrical systems and software. For the last two decades, usability and eco-efficiency in particular, have been a high focus of the latest development cycles. For the best efficiency of a farmer’s time in agricultural work, the tractor should work reliably as an all-around work machine, and with short service time consumptions. (Pennsylvania State University, 2013)

Simulation can be both physical and virtual, being an approximate imitation of a process or system. Physical simulation refer to physical objects which are substituted to the real thing. Physical simulation has been practiced for as long as one has been able to cognitively learn from one's own or another's environment. Virtual simulation is a younger part of the human life cycle, and mainly involves computationally and electronically produced models of real life. Virtual simulation can be used in engineering as a trial-and-error tool, alongside with computer aided design, to create a virtual model from a product. Using a virtual model and analysis instead of a physical prototype can lead to a significantly reduced lead time of projects. (Banks et al., 2001)

The product development (PD) is a process that begins with identifying the customer's need and ends with the customer's need. The product development process and the product development project should not be confused. The process is continuous and can be applied to many different product development projects. Instead, the project has a time-based start and end. (Pelin, 2009) The PD group of a company should essentially contract with the research group for certain technologies and product development priorities. Successful introduction of new products require more horizontal communication across functions and helps stimulate ideas. With the shortening of a products lifecycle during the last three decades, time to market is even more crucial. This leads to a focus on shortening and creating a more efficient PD process phase, along with decreased cost and increased quality and reliability. (Jacobs & Herbig, 1998) As part of the PD process, analysis of each step and design change is required to promote cost and time savings. The analysis can be done through simulation during the design process to evaluate the product performance before entering the market. Jensen (2016) brings up some topics if analysis of design is conducted through simulation:

- Simulation can determine the performance of a process
- Analysis and simulation are no longer high-tech endeavors
- Simulation can assist in decision making during the design process
- Simulation can accelerate time to market for product designs
- Understanding the different types of analysis is key
    - ➢ Direct optimization of design feature based on surface response model analysis
    - ➢ Structural and dynamic analysis of mechanical components and assemblies
    - ➢ Thermal analysis of systems

In the study of NAFEMS (2008), Up-Front Simulation is determined to be a key driving force for the paradigm shift in new product development. With conventional product development methods being costly, inefficient for competitive manufacturers, and time consuming, with a rush to producing physical prototypes that are tested, then rebuilt and retested. According to the Figure 1 paradigm shift’s simulation-driven approach, companies can perform simulations already in the concept phase of product development. This can lead to exploring alternatives at an early phase, while detecting flaws and optimizing product performance before a single prototype or even any detailed designs are created.

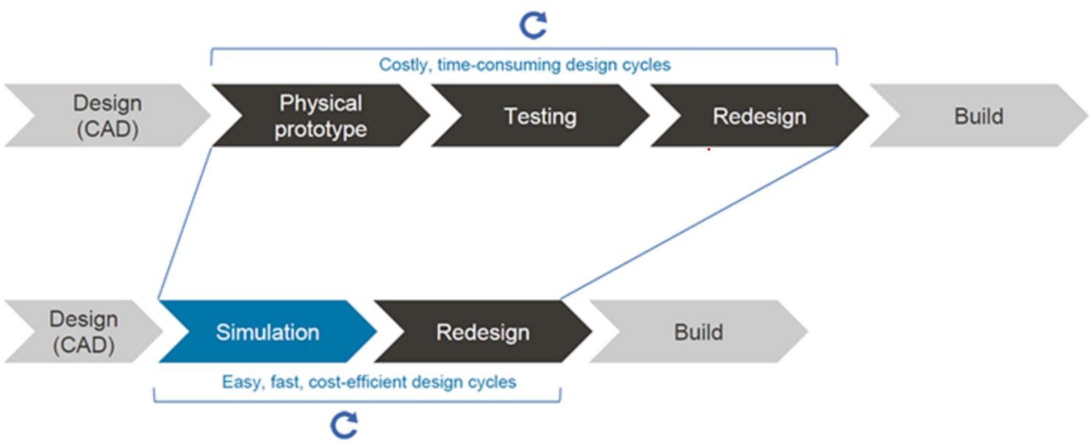

Figure 1: Two different simplified approaches for a product development process (SimScale 2018)

Valtra Inc. is the leading tractor development and manufacturing company in northern Europe, with a product range from 50hp small work machines to up to 405hp heavy duty tractors. One of the most important demands for a Valtra product is its capability to endure high dynamic forces and stresses, while maintaining the quality of an efficient all-around work tool. Therefore, the product development process has a high focus on physical prototypes and their testing in both demanding field work and laboratory test conditions. Using physical prototypes in the testing phase of new products is a highly expensive and time consuming process, and the future focus should be to reducing the number of prototypes built in a project. This must be implemented without any negative effect on product quality, while reducing the lead time for new PD projects.

1.1 Purpose

The tractor product development requires a lot of experience from the prototype level, both in the form of field testing and laboratory testing. The construction of prototypes is an extremely costly item in the budgets of product development projects, and there must be strong reasoning for building each prototype. Simulation is already providing a lot of help for proactive product development, and therefore everything does not need to be tested on physical models, bringing in cost and time savings. Simulation and physical laboratory testing can also be overlapped, so that rigorous product development schedules can be effectively utilized.

The first or initial designs in a PD process are traditionally derived from carry-over design, but also from past experience and best practices. These ways of design initialization limits creativity and leaves little room for radical innovation. Coming up with a fresh, ground-breaking design, without relying on best practices can be rather risky and can lead to poor end product performance. The only way to ensure the quality and durability of such a product design is to perform a high number of design iterations and prototyping until all the end customer criteria are met. This traditionally introduces a high number of physical prototype fleets and multiple time-consuming and expensive lab and field tests. (SimScale 2018)

In the corporate world, simulation is still mostly a tool used to verify and study fault situations after an experienced problem during prototype testing or field use. Of course, this is also useful for defining fault situations in support of design and product testing, but the full potential of simulation is in its ability to prevent fault situations in real life, and to support design from the product development concept to the final validation tests. Finally, the end customer should always be considered, since he is the one who should be able to invest and place his confidence and trust in a proven and a reliable agricultural machine. As is said in a 2008 consortium report of NAFEMS (2008), the automotive industry has to cope with the following obligations; pushing innovative technologies, reducing development times, and reducing costs.

1.2 Reference framework and research problem

Research data and its simplified theoretical implementation studies are needed on the applications of computer simulation to enable current and future product development projects exploit its potential and possible project cost savings. In companies, simulation has already been deployed for most product development projects, regardless of the area of science. This can be utilized in almost all industrial and infrastructure project planning and preparation areas. However, only a fraction of the potential for simulation is still used, and it is not yet a sufficiently large part of design support and preparation. More efficient implementation can prevent notable design faults and false approaches during a development project lifecycle. (Kortelainen, J. et.al. 2015)

The theoretical framework of the research is built on the objectives and the table of contents of the study. The starting point for the framework are the values of the organization, the vision, and the strategy on the basis of which the map for the use of simulation is built. It is also part of the frame of reference to define success factors for each product development area that supports the strategic goals of product development. To implement simulation in a larger scale into the company’s product development process, a project would be most probably needed with further research into the subjects and methods of simulation that can be utilized in decision making. As an outcome, simulation could be integrated into a PD process as a strategy. Thus the research problem of this study is: why and how a model or map of simulation work in a company’s PD strategy can be widely embedded and utilized.

1.3 Objective and research questions

The research draws on the existing theory and practical experience of business and universities in product development and simulation. This study searches for and analyzes information to create a large toolkit of modern simulation methods and tools that, after further studies and comparisons, could replace individual or whole series, either partially or completely, of a tractor prototype. It should be noted, that a product development cycle for one project can include several prototype series, and it is not expedient to try and replace all the machines with simulation experience. The objective of virtual simulation should be to prevent design errors, and to boost cost savings in prototype construction and tractor development in the long run. Figure 2 shows a simple view of the possible optimizations, innovations and savings possible through an iterative simulation/design/validation/analyzing loop, with the main aspect being the prospect of Modeling and Simulation (M&S).

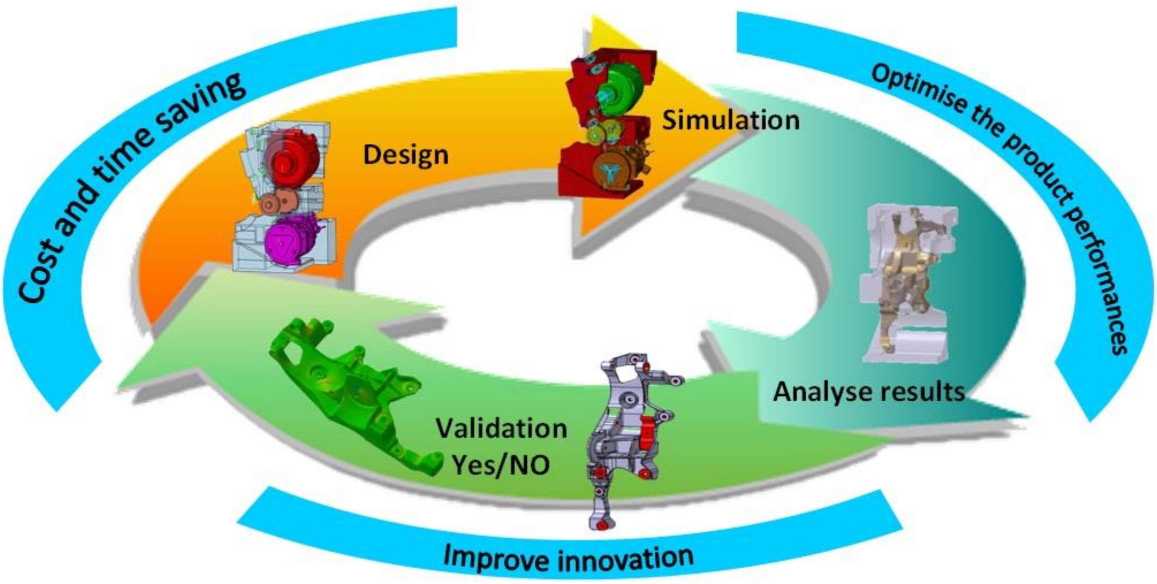

Figure 2: Simulation as a part of a development loop (Wang 2018)

The main goal of this study is to summarize and create a map of virtual simulation to increase product development performance and decrease PD project related costs. The charted tools are to be categorized into their own compartments that run in parallel with the product development components of a project content. The aim for the study is to collect qualitative research information about the possibilities of virtual simulation. In the practical part of the research, the information gathered is intended to be used as practical knowledge and as a basis for the exploitation of simulation in the development and validation of a tractor.

The research questions to achieve the goal are formed into the following items:

- How much and what parts of the tractor's product development and testing could be simulated?
- Are there proven issues in the field with relation to passed validation tests that could be taken into account with simulation?
- What are the most time and cost consuming areas of development that could be assisted with simulation?
- How can simulation be integrated into product design, design validation, and design risk management?
- What applicable simulation methods are not yet in use?

1.4 Subject boundaries and hypotheses

The study focuses on the mechanical engineering of the product development process at Valtra Oy’s Research and Development (R&D) department in Suolahti, Finland. The reasoning behind choosing the focus on the mechanical engineering is related to the university study background of the author. The study will be performed in a reliability engineers’ point of view.

This study does not address the simulation of electronic devices or software (code). Virtual reality simulation is also omitted from the content of the study, as the study would otherwise be too extensive. The study does not include any practical sections intended to measuring or utilizing the simulation tools, models, or test settings that may be mentioned in the study. Also any relationships to automation solutions, logistic operations, production lines and other manufacturing processes are not accounted for, but can be partially touched on in some occasions.

Based on the background, research questions and boundaries, three research hypotheses are formulated in order to be discussed in the conclusion and discussion chapter of the thesis.

The main hypothesis is that product development cycles can achieve long-term cost and time savings, such as minimizing prototype manufacturing, by investing in simulation skills and tools.

Secondary hypothesis is that modern simulation tools can be used to prevent conceptual design errors with the aid of previous product development cycles and given project pre-information.

The third hypothesis is that simulation grants possibilities to support product development processes on a larger scale than its current state, especially with the aid of design validation plans (DVP) and risk management such as DFMEA (design failure mode and effect analysis).

1.5 New scientific knowledge and applications

New knowledge and a whole view of the tool spectrum in the field of simulation and agricultural machinery research and development is expected from the research results, both through increased peer-to-peer data and increased research knowledge as a measure of reliability and efficiency of design. From the results of the research, it is expected that virtual simulation already has high prerequisites and possibilities to be a design and end-customer support throughout the product development process and end-product life cycle.

Based on the results, it is expected for one to be able to make group-level suggestions for increasing the number of simulations with man work hours and pre-described tools, citing cost-effective product development validation, reduction of the number of prototypes assigned, release of resources for other product development activities, and preparations of product development materials. With the aid of the issued map of simulation, further work could be issued to create a framework for a long-term plan to increase simulation in product development, especially to support design and validation. The results to be achieved give added value and reliability to private and public factors, for further research around the subject, and for the development of the university world and subjects taught for future generations.

2 METHODOLOGY

In this chapter, the methods of the study are discussed.

2.1 Qualitative method and description of results analysis method

This study provides qualitative material on the simulation capabilities of mechanical components and entities. The research material consists of scientific research on simulation and product development, practical know-how, subject books, and journal articles in relation to physics science. The research is also supported by an ongoing, but early-stage product development project. As a method of analysis, the validation of research material is used, as well as expert and project interviews.

The study uses a guiding approach, i.e. to determine what kind of the object should be. In this case, it will be necessary to define the subjective perspective on which things are considered. A guiding nomothetic study will draw up guidelines or plans to improve the subject or other similar items, but will not take practical action. (Routio P. 2006.)

An iterative guiding process is used during this study, including the following step-by-step process:

1. Evaluating the state of affairs, where the situation and needs for improvement go through.
2. An analysis of the interdependencies and opportunities to change things.
3. Synthesis, i.e. a suggestion to improve the condition (the study does not include an experiment on improvement).
4. Evaluation of the proposal. (Routio P. 2006.)

Figure 3 depicts the procedure of what data and knowledge is to be studied and further analyzed.

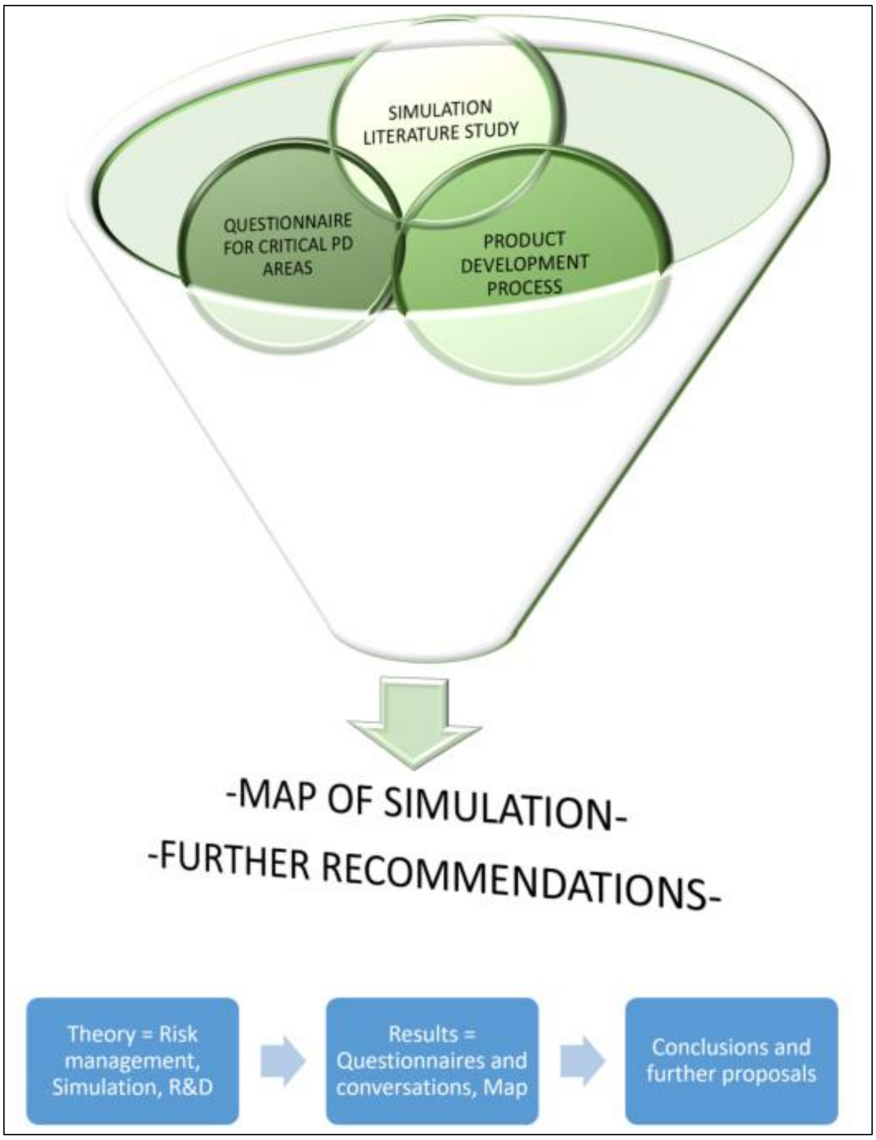

Figure 3: Method model and process for the study

2.2 Questionnaires and interviews

A questionnaire is a convenient method, if the study design is clearly predetermined, and will not change during the course of the study. One can also ask quantitatively measurable or otherwise exactly determined physical things. If a researcher has a well-defined group of problems to be investigated, it may be most effective on this basis to pre-formulate questions and stick to them well. In this case, quantified summaries of the responses can also be easily obtained and can be statistically analyzed. Such a uniform standardized or structured inquiry is usually carried out either as a written query or as a form interview. One must be careful with the questionnaire not to confuse two different issues with one question. First of all, it would make it difficult to answer the question, and the worse disadvantage is that the researcher does not have any means to determine which question has been answered when analyzing the answers. As a rule of thumb, one may consider that the question should be short and without the secondary phrases. (Routio P. 2006)

In this study, a survey is formed for experts and designers in different modules to gather information about the product development process at Valtra. With the survey as a first phase pre-study, empirical data is formed as a basis for further discussions to get an overall picture of the process. The key points are to gather data on used simulation methods, and to compare it to laboratory related test loads. With the data and thoughts from the survey, an analysis can be done to determine the starting point for further implementation of simulation. The second phase consists of discussions between module designers, and simulation and validation experts, with the common goal of introducing the questionnaire data, and provoking thought sharing between teams. Discussions are then summarized to further improve the details of the PD simulation map. Interviews here are semi-structured, since a semi-structured interview and discussion is more pre-defined and the interviewer has prepared a set of open questions from the pre-study material. All survey related information and discussions in this study are qualitative, since knowledge and understanding about the product development process and simulation are more important than a large number of data.

2.3 Validity and reliability

According to Routio (2006), validity can be both external and internal. External validity is better when the researcher does more real conclusions from observed situations or sources. In order for the researcher to draw the right conclusions, he or she is required to have solid knowledge of the subject. When the researcher sticks closer in the materials own say, the risk of misinterpretation decreases and the external validity of the research improves. Internal validity is about the methods used to measure the right things that were intended to be reviewed in the first place.

The validity of the study is verified by source-critical review, and is reflected in the comparison of the sources of literature and know-how, thus eliminating random results. The large number of sources and the critical review of each provide a sufficient basis for determining a study’s reliability.

Any given statements from Valtra Oy experts and specialists can include internal terms that are not anyhow generalized or freely translated. However the relative dependency of freely spoken terms has an impact on the reliability of the study material and conclusions and is discussed further in the report on chapter 5.

3 THEORETICAL FRAMEWORK

In this chapter, the theories of tractor product development, design reliability and virtual simulation are studied.

3.1 Tractor product development

A tractor is a versatile machine and is mainly intended for pulling different types of machines. Typically, tractors are used on farms, but they are also used, for example, in forestry, road maintenance, snow work, and other various environmental management activities. Usually powered by a turbocharged diesel engine, and a 4-wheel drive automatic transmission for high traction and pull force, which is a requirement for efficient and capable agricultural work. A safety cabin is mandatory for a tractor, but also a three-point linkage for attaching implements, and a tow bar for towing a trailer. A front loader is a versatile accessory that is firmly attached to the frame of the tractor. The front loader can be equipped with a range of work equipment, such as a snow plow or a hydraulic grapple for handling large hay bales. According to Woo S. (2017), “agricultural machinery such as a tractor is used in the operation of an agricultural area or farm.” The hierarchical configuration of agricultural machinery usually consists of an engine device, power supply unit, hydraulic unit, electric devices, front and/or rear linkages, front and/or rear PTO driving unit, and other miscellaneous parts. The reliability block diagram of a typical tractor appliance system contains over 4000 blocks, including the parts of each system (see Figure 4). The vast quantity of different systems and components brings a huge demand for virtual simulation to validate the product development in more detail and with high repeatability in and iteration process.

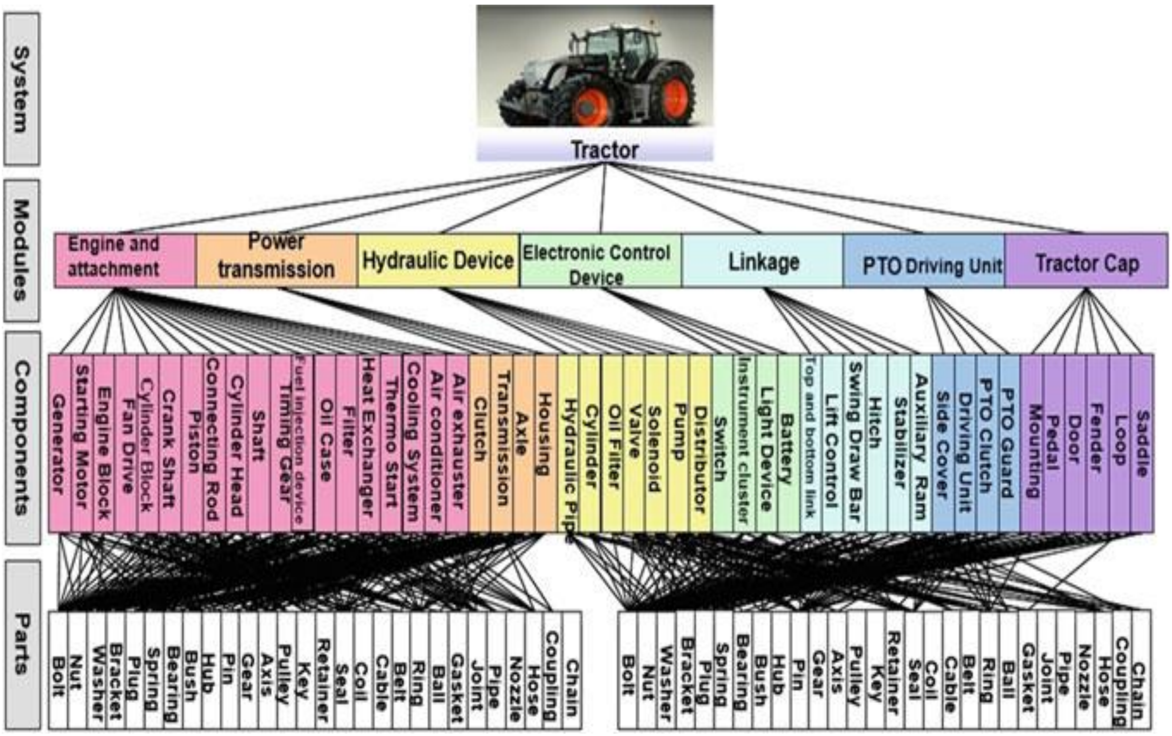

Figure 4: Breakdown of a tractor with module categories by one approach (Woo S. 2017)

Product design for large machinery, such as tractors, is a highly complex process, with requirements, constraints, and multiple objectives all of which need to be successful for the end customer to be satisfied. The important factors that the design team needs to keep in mind include safety, functionality, cost-efficiency, durability, and aesthetics. Other design aspects usually are quantifiable and they can be accurately tested and validated, but the aesthetic appeal of a product might not be. (SimScale 2018)

3.2 Product development cycle in general

One of the main tools of new product introduction (NPI) projects at Valtra is the AMPIP 2.1 process, which is meant to harmonize the operations and operating practices of AGCO's subsidiaries. The AMPIP process consists of 6 main phases illustrated in Figure 5, with the main focus to control and monitor the degree of use of project resources and the timely completion of tasks and deliverables, as well as the monitoring of operational objectives and risk management.

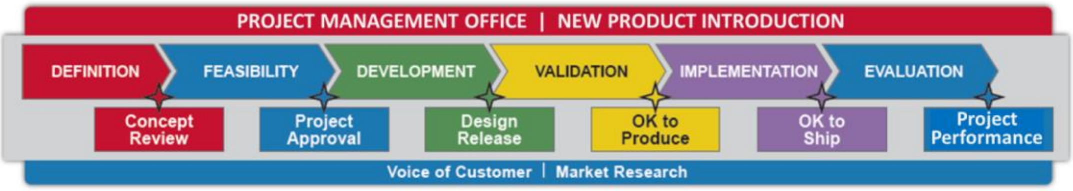

Figure 5: Six phases in AGCO AMPIP 2.1. PD process (AGCO 2019)

The AMPIP process encompasses all aspects of the product development process, including conceptualization, design, manufacturing, procurement, marketing and aftermarket, training, and project success assessment. Validation is presented as a separate step after the Design Release (DR) port, but design validation is in fact a sub-process that starts with the definition phase and continues up to the OK to ship (OS) port. (AGCO 2019) The step-by-step product development process for managing the risks of product development projects is a good tool. Information on said various activities, is collected in stages, and compared to the set goals. In this way, technical and financial risks are reduced by continuing a project that does not have potential customers or whose financial viability is not sufficient. If the risk management is well designed, the uncertainty of project implementation will be reduced and at the same time the overall risk of the project will be lowered before the project-related investments start to increase significantly (Cooper, 2011).

3.3 Reliability design of mechanical systems

Because new products are often recalled worldwide in varied quantities, product reliability becomes an often used term for everyday life. Product quality shows a key to the success of the current global competitive market. If the product quality does not meet the expectations of the customer, the product will not last long on the national and international markets. Therefore, it is important that the product design team understands the expectations and voices of the customers. Product reliability is the product's lifetime guarantee. Tools for reliability, such as bathtub, MTBF (average time between failure) and failure rate, have been established as standard methods for measuring reliability during and after a PD process. To implement such methods also need basic knowledge about probability and statistics. When used, reliability could be determined by analyzing data from the market and PD lifetime. Performance statistics, as illustrated in Figure 6, such as high response, energy efficiency, low noise, high reliability, long life and latest hardware design, contamination resistance, low cost and compact portability are but a few aspects for a product in surviving in a global market environment. (Woo S. 2017)

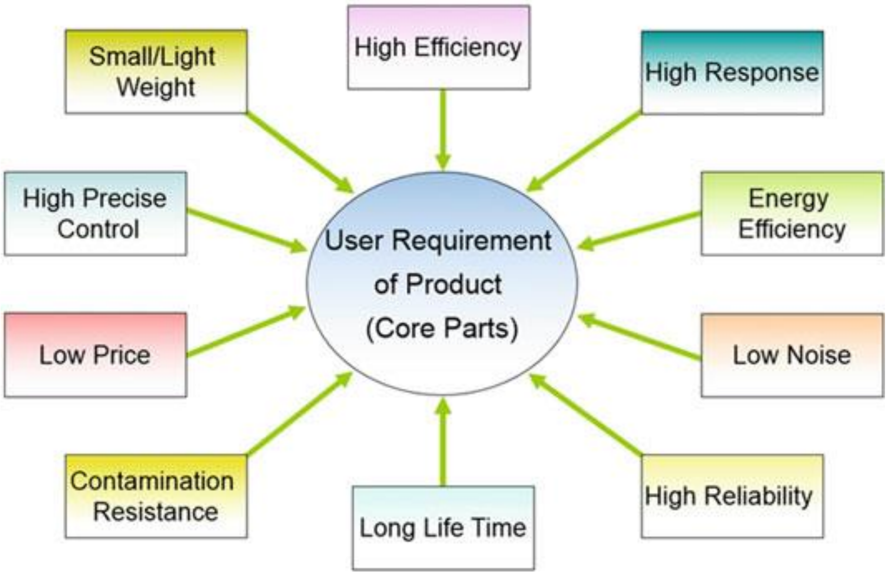

Figure 6: General customer requirements of a product or component (Woo S. 2017.)

3.3.1 Risk management and design validation

Design Validation is a process that can be used to verify that the design of an optimized product and process meets customer requirements. Design validation consists of product design validation, manufacturing process validation and production validation, but this study touches only on product design validation and should, from the product development perspective, consist of the following items (Yang 2009):

- Validation of functional performance
- Validating the environment requirements
- Validation of reliability requirements
- Validation of operational requirements
- Validation of safety requirements
- Interface and compatibility validation
- Validation of maintenance requirements

For all parts of the system, there is no need to perform each validation step since the validation requirements and their importance is varied for different parts of the system. The content of the design validation process should be compiled by selecting the most appropriate areas from the list above. (Yang 2009)

3.3.2 Failure Mode and Effects Analysis

The FMEA is one of the most commonly used risk management and analysis method in engineering. The tool is used to identify the possible failures and risks stemming from an NPI project, and furthermore to predict failure effects and relevance in the product. The FMEA allows to project to identify potential problems in the product before they reach the final customer. FMEA is usually started already in the concept phase, and should be updated and improved during the whole PD process. The complete system can be studied and controls be taken with both Design FMEA (DFMEA), and Process FMEA (PFMEA). (Segismundo A. 2008) DFMEA can be conducted when new systems, products or processes are being designed, existing designs are being changed, or when carry over designs are used in new applications. (Pawar, G. J. 2015)

When FMEA studies are made, all the components and modules are considered. The process consists of three measures, the probability of failure occurrence, severity of the failure, and the capability to detect the failure before its occurrence. The value when these three points are multiplied, results in the Risk Priority Number (RPN) value. FMEA usually prioritizes the most critical failure modes, but is also requires the analysis of each component or module in the system. The analysis of all the parts can require a substantial amount of resources if done correctly, so the method is most of the times implemented with at least some modifications. (Segismundo A. 2008) An example of a DFMEA analysis in Figure 7, where SEV is severity, OCC is occurrence, and DET is detectivity. Severity in the DFMEA is a measure of the importance of effect of the failure mode. Occurrence is the frequency of a particular failure mode, and can be referred to as probability of the cause of the failure. The less the time between failure, the higher the occurrence rating is. Detection number measures the probability of detecting the root cause of a particular failure mode. (Pawar, G. J. 2015) The higher the RPN value is, the more should be focused on the mitigation plan of the failure mode. Usually a DVP list is derived or updated from the mitigation plans that arise from FMEA.

Company				Failure Mode and Effects Analysis						FMEA Number Indentification			Page of				
Part Number (s) or Part Family				Design or Process Responsibility				Prepared by and their Title					Telephone # / Email Address				
Process/Design				Team Members				FMEA Creation Date					Latest FMEA Revision Date				
Process Step/Input or Design Item	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) / Mechanism(s) of Failure	OCC	Current Process Controls to Prevent Failure Mode	Current Process Controls to Detect Failure Mode	DET	RPN	Recommended Actions	Person Responsible for Actions	Target Completion Date	Actions Taken	SEV	OCC	DET	RPN
									0								0
									0								0
									0								0
									0								0
									0								0
									0								0
									0								0
									0								0

Figure 7: An example template of a FMEA table (SixSigma Material)

3.3.3 Design Verification Plan

Design verification usually consists of a series of tests and analyses, both by examining and providing evidence, that the design output meets the design specifications given for the PD project. A design verification process is essential during any PD cycle, to ensure the designed product meets its intended use and known customer validation requirements. The validation tests include (Yang 2009):

- Reliability testing
- Functional testing
- Validation testing strategy
- Testing for variation
- Safety and regulation-related testing
- Testing for interface and compatibility
- System, subsystem and components testing
- Materials testing
- New technology testing
- Validation activity planning

Figure 8 depicts a flowchart of a product design validation process that illustrates the interdependencies between design requirements, design model analysis, and testing. It can be concluded from the flow chart that to manage a product validation plan, one should start by compiling a comprehensive list of requirements based on the product requirements.

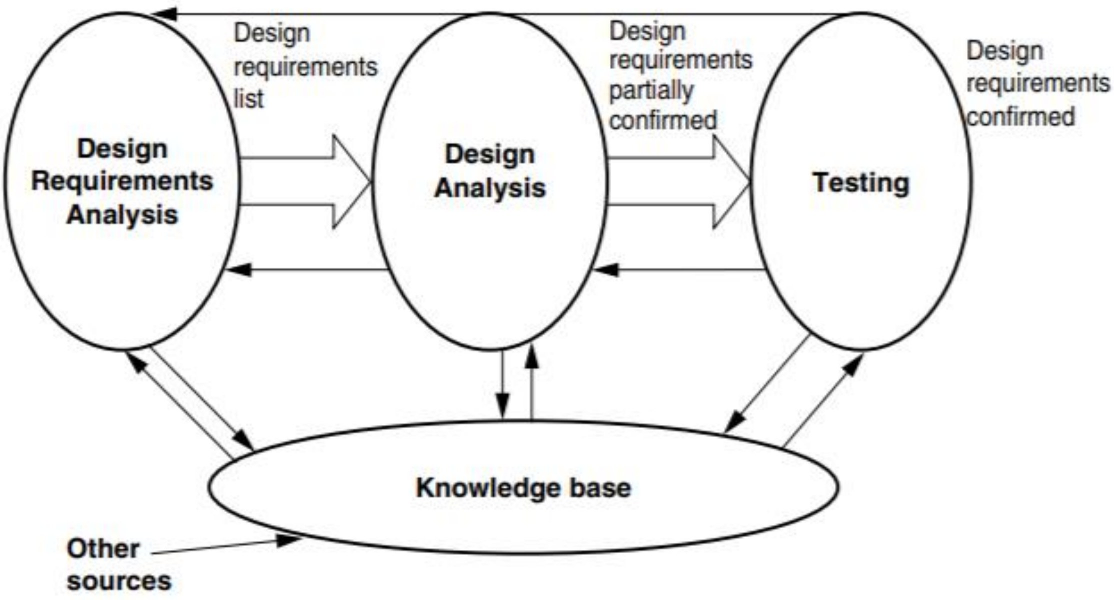

Figure 8: A flow diagram for design validation (Yang 2009)

The design verification and validation directly influence production performance and customer perception of the product quality. Processes for building the design verification plan (DVP) include a full range of tools employed during digital design phase, and methods that are deployed during the prototype testing phase in laboratory and field conditions. (Maropoulos et.al. 2010)

3.4 Product and Simulation Data Management

An increasing volume of applications requiring modelling and simulation in a PD process produces even more challenges for data management and integration of data sources. To effectively and seamlessly integrate all the data required for model composition and results of simulations into the product process, Product Data Management (PDM) systems have been introduced. The PDM data can be any product documentation, bill of materials, or design data such as drawings and 3D part files. In addition to all the data gathered into the

PDM system, the complexity of the data and any related information increases due to a high number of revisions, versions, and iterations of the design and simulation objectives, which are needed to understand the development of the product better and learn also from the previous projects that are already finished. In this trend, the bottleneck of the process tends to be the engineer himself, with a limited capacity of information processing and memorizing. This issue can be somewhat detained through the abstraction level of the managed data, with the best solution being to transforming the plain data into information like in a semantic web. (Kortelainen, J. 2011)

Often the data of design and testing teams and tools are separate or even isolated from each other, with the used tools being specialized in the engineers own area of expertise. Simulation Life-cycle Management (SLM) tools are used to seamlessly combine design and simulation tools with a same formalization process. The use of SLM can prevent design issues from the early phases of a PD process, and to enable design data utilization also in later stages of the product life-cycle. Simulation Data Management (SDM) is also included in the PDM loop, as seen in Figure 9, with capability integration of several different and important PD process phases and tools linked to each other. SLM having the main focus of virtual world within the product life-cycle, narrowly collaborating with the Product Life-cycle Management (PLM). (Kortelainen, J. et.al 2015)

Figure 9: Product and simulation data management during a product lifecycle (Kortelainen, J. et.al. 2015)

The SDM system's base functionality is to provide the management process of simulation data, and information related to the context. Any SDM strategy should not be developed without considering its relation to the company's PLM strategy. The SDM system needs integration with simulation applications, but also with the PLM system. When simulation data is effectively managed, a company can gain large development time, quality, and cost savings in, for example, repetitive simulation processes.

3.5 Virtual simulation

Simulation is usually explained as an approximate imitation of the operational functions of a system. Simulation can be used to show effects and ends from alternative conditions and actions implemented into the studied system, while the system itself may or may not even exist yet physically. Thus the designer of the system does not need to have access or engage with a potentially dangerous prototype or mock-up to find out the specific details or features that need validation. "CAE (Computer Aided Engineering) tools play a key role in creating an improved design by simulating and analyzing new vehicle concepts intended to fulfill these requirements. They enable optimum use to be made of information in the various design phases, from the conceptual design phase to the detailed series-development phase.” (NAFEMS 2008). Such is the case still today, though a lot has happened with simulation tools already after the 2010th century.

In new product development projects, virtual simulation tools are often introduced to utilize more the benefits of cost and time efficiency. What is often also regarded is the virtual experimentation as a way to overcome the cost and time limitations of physical experimentation methods according to academic literature. According to Becker (2005), these are not the only benefits of virtual simulation, but they also improve the possibilities of more innovative designs, “under the condition that the possibilities they provide are matched with organizational and management structures required to realize these possibilities”. This is not really a technical issue, but rather an organizational challenge.

With simulation in general, and for example the flow calculation (example in Figure 10) needs of tractors are very similar to those of the automotive industry. However, the aerodynamics of the body of a personnel vehicle have a much lesser significance as that of a tractor, for the driving speeds are generally lower and air resistance does not have as much of an effect to fuel economy. Typical calculation cases, on the other hand, are engine air intake and exhaust flow, assessment of comfort and especially cooling. Also the engine inward flows and combustion reactions are in themselves essential. (Makkonen, P. 2016)

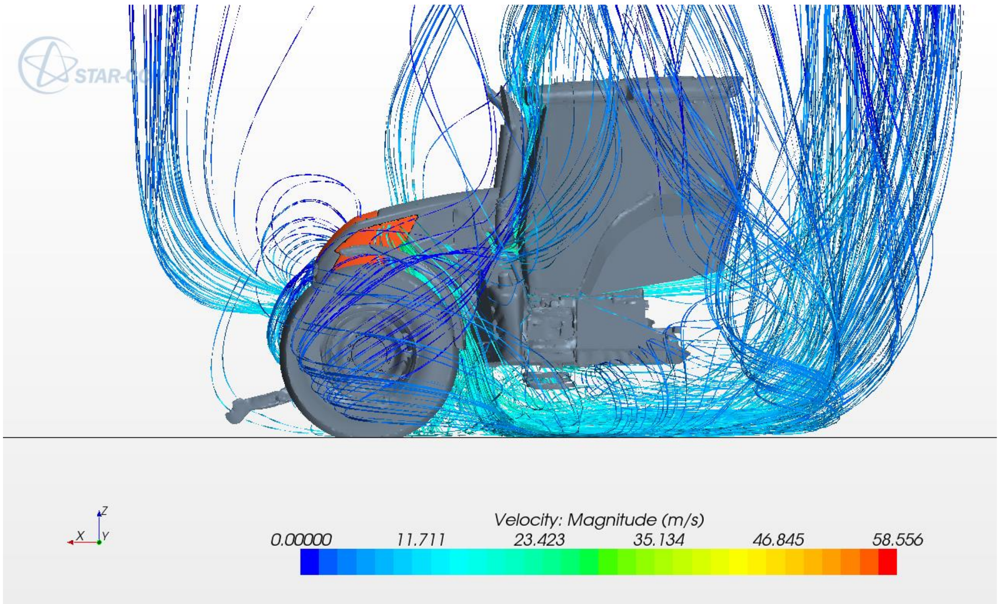

Figure 10: Air current lines around a tractor, simulated with Star-CCM software (Makkonen, P. 2016)

Computer-assisted virtual testing and simulation can be used to analyze a variety of applications. Mechanism-based simulation models are usually commercial computer software and, depending on the software, they have been developed to analyze phenomena in a particular application area such as mechanical engineering, electrical design, or electronics design. The most commonly used mechanism-based simulation models are mechanical simulation, fluid dynamics simulation, electrics and electronics simulation, and many other simulation models such as product development process, financial and economics simulation models. (Yang 2009)

The mechanical design of components and systems is usually done by CAD (computer-aided design) software, which can be used as a starting point for making CAE analyzes such as stress and vibration analysis. FEA (finite element analysis) is a computer-based computing technique that can be used to assess, for example, the influence of mechanical factors such as forces, deformations and material properties on body strain and strength. The FEA method for analyzing the flow and other properties of gases and liquids is called the Computational Fluid Dynamics (CFD) analysis. For example, CFD software can be used to analyze vehicle engine internal flows or cooling system flows. (Yang 2009)

3.6 Simulation methods

The most important parts of product development computerization methods through software are Computer-aided Design (CAD), Computer-aided Engineering (CAE) and Computer-aided Manufacturing. The chart in Figure 11 depicts the computer-oriented environment with these different components. The structure presents useful tools in creating and modifying industrial properties or products.

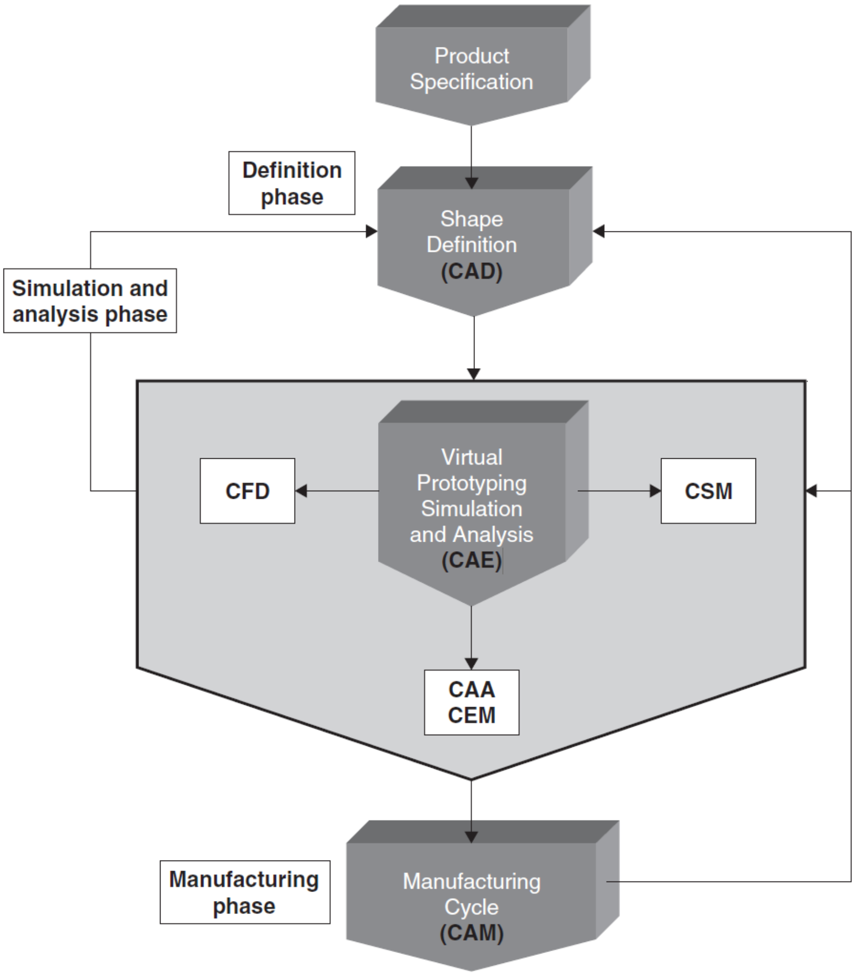

Figure 11: The structure of the virtual prototyping environment. (Hirch 2007)

To successfully use any CAE tools, a CAD model needs to be created and/or assembled first. The model will then be the input for any CAE simulations. The CAE simulation results are then used as input in re-designing the models previously used, and this cycle is repeated iteratively at least three times to receive enough data for optimal behavior of the model. When the desired design objectives are achieved, CAM software is used to simulate any manufacturing processes, such as forging or molding. (Hirch 2007)

The motivators of using CAE tools usually involve money saving in product development, or getting the necessary new knowledge about the designed system without the need to test it with a prototype or a simple mock-up. According to Kortelainen et.al. (2015) the benefits can be numerous, if taken into consideration the abilities of implementing a concurrent engineering process or gaining more knowledge about the details of the product or system under development. Designing high-quality products and getting them to market quickly while minimizing the engineering costs, the computational approach of CAD and CAE provide the means of optimizing a multi-objective challenge in a product process. While methods today are even more specialized, the role of a design engineer can change over time while the different CAE tools are being integrated into the CAD programs. This allows the design engineer to iteratively compute at least the more simplified calculations. (Johansson et.al. 2012)

3.6.1 Finite element method

The Finite Element Method (FEM) is a widely known and accepted computational method of solving structural problems in engineering. With an adaptive virtue, the FEM provides a simple way for solving complex problems in heat transfer, fluid mechanics and structural analysis. The FEM can be applied into the most complex of geometries, but also with many mixed materials and their boundary conditions. The method is also suitable for time dependent problems and nonlinear material behavior, but the FEM is deterministic by nature, thus having a limited possibility to describe the system characteristics universally. (Arregui-Mena 2014)

The FEM method was already developed in the mid-1900's to calculate and analyze the expected durability of physical constructs, systems, and components. The FEM as a numerical solution is used when, for example, analyzing the durability of different geometries, and when partial differential equation becomes too complex to solve analytically. The FEM method produces a numerical approximated solution for the equation. The practical engineering application of the mathematic FEM methodology is referred as FEA. (Adams, V. 2006).

The FEA calculations have usually been performed with a separate software such as ANSYS or ABAQUS, but more and more the CAD software providers include an integrated FEM solver into the service package. The separate software is better in handling more complex systems with more calculation performance and tighter mesh-models, and the integrated FEM solver is usually intended for simplified structures with mesh-models being created automatically. Both give fairly similar results, but the separate solvers produce more absolute values to better determine the most critical areas in the studied model. (Bathe K.-J. 2014)

A FEM simulation process needs multiple design-FEM loops. To further accelerate the analysis loops, a CAD adaptation model is required, consisting of the CAD model geometry simplification by eliminating any unnecessary details or faces regarding simulation. These might be for example any holes, fillets, or chamfers. A hybrid method for simulation model simplification is explained in Mounir's (et.al. 2013) comparison study, where with the hybrid method the computing time is reduced by the elimination of non-boundary conditioned geometric details shown in Figure 12. An added amelioration of the result precision highlighted the hybrid methods' efficiency.

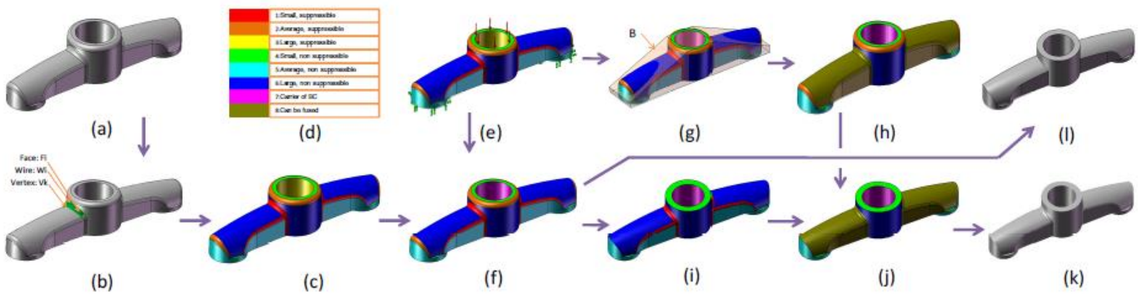

Figure 12: Simulation model simplification stages from (a) to (k) using a hybrid method (Mounir et.al. 2013)

3.6.2 Computational fluid dynamics

Computational Fluid Dynamics (CFD) is was a product of research laboratories and universities, and is a type of CAE simulation used to analyze fluid and thermal transportation. Significant efforts have been made in the field of combustion engines, in which the benefits of CFD for the design of automotive components was demonstrated. Now

CFD plays a major role, for example, in the automotive and other industries, such as aerospace and heavy machinery. (Tamamidis, P et.al. 1997) Other more specific uses can be in analyzing the air or liquid flow through turbines, and predicting pressure drop in exhaust systems.

According to Anderson (2009), CFD derives from the fundamental governing equations of fluid dynamics:

- Continuity
- Momentum
- Energy

All fluid dynamics are based upon the three fundamental physical principles, or mathematical statements that form the continuity equation, Navier-Stokes equation and the energy equation. The equation set consists of conservation of mass, conservation of momentum, and conservation of energy.

The Finite Volume Method (FVM) is a common approach in CFD, with advantages of being able to calculate high Reynolds number turbulent flows and other large problems. In FVM, the governing partial differential equations, like the Navier-Stokes or turbulence equations, are in conservative form. Then the equations are solved over discrete control volumes. FEM is also applicable to fluids, but requires special care to ensure a conservation solution. However, it is much more stable than the finite volume approach. (Surana et.ali. 2007) CFD is usually used for both basic mechanical research and engineering design, but also for pure theory and experiments about fluid dynamics. (Anderson, 2009)

As an example, Figure 13 shows a gas circuit breakers' external air domain, which is analyzed with CFD to predict temperature rise in various components at the design stage of the system. The CFD analysis can help in (Pawar et.al. 2012):

- Testing the components virtually with different design alternatives and selecting the most optimal design variant
- Design alternative(s), finalized by prediction, can then be manufactured as a prototype and furthermore physically tested, leading to the ability to limit the number of physical tests.
- Reducing NPI cycle times

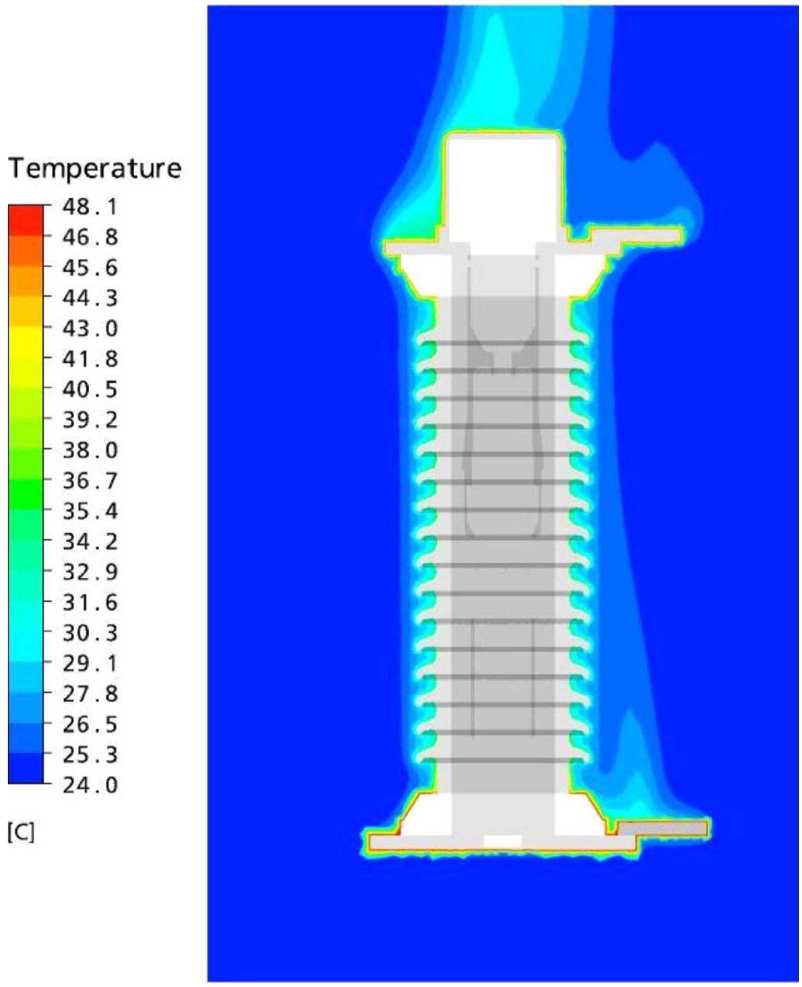

Figure 13: CFD calculation of the temperature distribution of an external air domain breaker (Pawar et.al. 2012)

3.6.3 Multibody simulation

A multibody system (MBS) is an assembly of several bodies connected to each other by different joints, and they are affected through internal or external forces and can have a different level of complexity. A multibody system has two main characteristics, mechanical components with large translational and rotational movements, and kinematic joints that describe the constraints and restrictions on the relative movements of the bodies (seen in Figure 14). The bodies can be considered rigid or flexible, with the rigid bodies assumed to have only small deformations caused by the motion of the body, and flexible having an elastic structure. The body parts are composed of a collection of material points. A rigid structure can translate and rotate, but its shape cannot be changed with a full description of six generalized coordinates. A flexible body can have as much of generalized coordinates that is needed to describe the deformations along with the nominal six as in a rigid body. The body and its parts are connected by joints, usually devices such as bearings, rod guides, or linkages. The joints are considered either as revolute joints, translational joints by the mathematical point of view, according to the relative degrees of motion that is permitted in the system. The dynamics of a multibody system has a long history, and is considered to be based on classical mechanics. Multibody systems can be used to analyze both mechanical structures, and biological (such as human body) movements likewise. They can be used to frequently prototype a control system, and are used in applications such as robotics, medical systems, and computer games. (Flores, P. 2015)

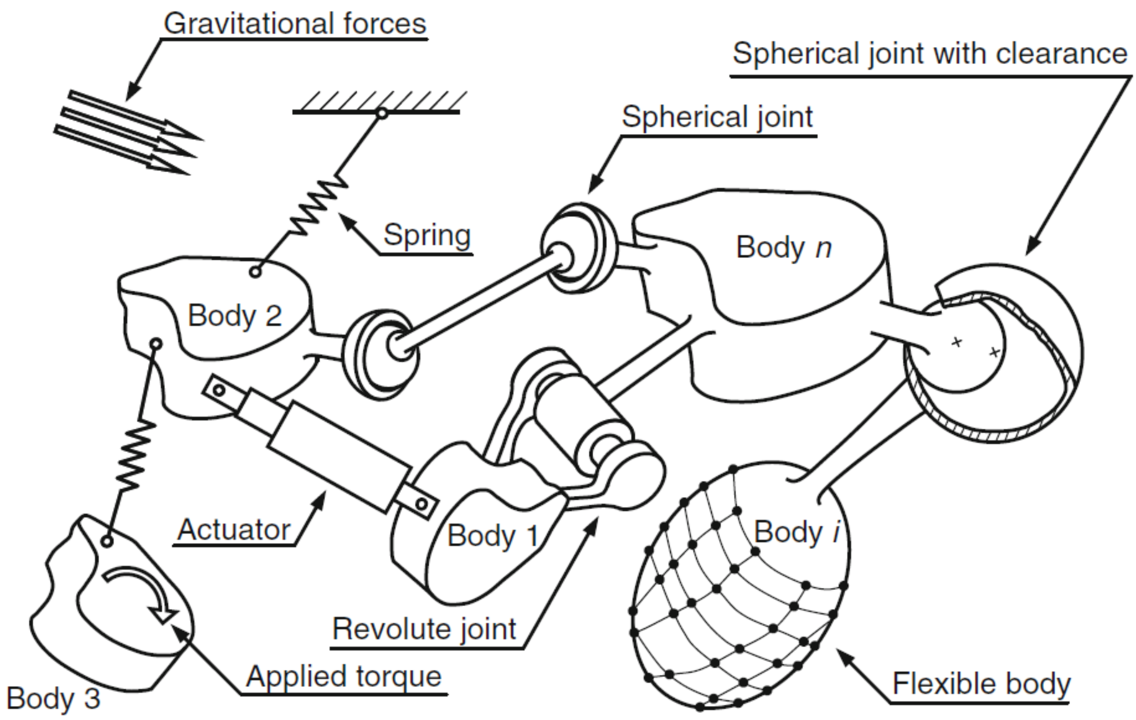

Figure 14: A multibody system, with the most significant components being the bodies, joints and forces elements (Flores, P. 2015)

Multibody systems methodologies primarily include two main phases of work, at first the development of mathematical models of multibody systems, and second being the implementation of computational procedures used to manage the simulation calculation, and the global motion analysis and optimization. (Flores, P. 2015)

Multibody system simulation is an attempt to predict a mechanical systems’ behavior, with a variety of connected bodies that can move relative to each other. Typically a multibody system simulation consists of three different phases, pre-processing, solving, and post-processing. (Kortelainen, J. 2011)

3.6.4 ROPS simulation

The Rollover Protection Structure (ROPS) is one of the main safety-related tests that are mandatory for heavy machinery product development process. Heavy duty machines are particularly prone to loads resulting from rollovers on a slope or uneven surface, and hits by falling or otherwise externally moving objects. In such situations the most important protective structure is the operator environment. In the case of an accident, the structure of the cabin should transmit the forces of a rollover and absorb enough of its related energy. Especially the forces of lateral force load, vertical force load, and longitudinal force load. (Karlinski 2012)

Usually the ROPS tests are performed by a test lab authorized by the local authority, but since the tests are critical to pass acceptably and must be done with series-like design, the structure should be pre-tested. The pre-test is nominally done with a likewise test either at the authorized test lab for verification, but it can be performed also with simulation. Computer simulation has had a large impact on the design of rollover protection structures and frames of tractors. With simulation, it is possible to do several iterations with different virtual methods, compared to the destructive physical tests that consume more time and funds. (AGCO 2019)

In the ROPS test, the cab structure is exposed to relatively high loads. Experience shows that the behavior of the structure in the test is very nonlinear and that major permanent deformations occur. For these reasons, it is clear that obtaining useful results requires consideration of non-linearity also in the calculation. In general, non-linear behavior can be attributed to three different factors: material properties, large geometry changes, and boundary conditions. Because the computational geometry is quite complex and therefore requires a rather dense element network to accurately model it, the computational times of nonlinear analysis are expected to be relatively long. In practice, the available computing capacity determines the model with which the calculation can be reasonably performed and whether simplifications must be made to keep the calculation time reasonable. This should be taken into account if the results are to be used in practical design work. (Salonen 2009)

A ROPS simulation as seen in Figure 15, is normally FEA-based simulation, but regarding calculation it can still differ from static strength simulations. Implicit methods are used in FEA to invert the matrix in order to find a reasonable solution for static loads. Explicit calculation methods are used instead, however, in ROPS simulations since they need to account for big deformations, and plasticity and hardening factors of materials. Hardening varies with the stretching velocity, which means the material properties and their stretching effect needs to be considered with the short period of time that it is simulated. This is why behaviors cannot as easily be as intuitively predicted as fatigue analysis and static strength calculations. (Johansson et.al.2014) Almost all the simulation programs have FEA capability with explicit calculations, but some programs like ANSYS are more capable for M&S, and more suitable for ROPS testing. (Salonen 2009)

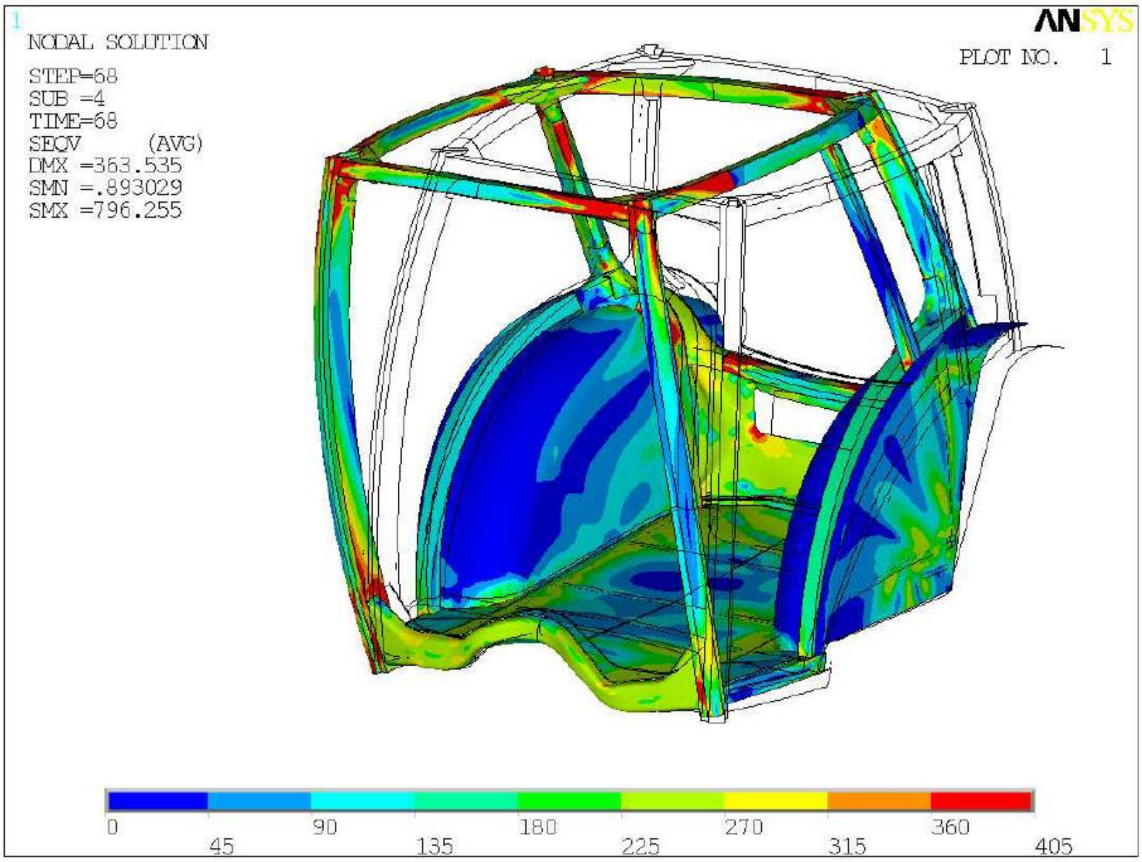

Figure 15: Tractor cabin transformation and von Mises stress calculation in an external load situation (Salonen 2009)

3.6.5 Noise and vibration

The understanding of NVH (noise vibration harshness) generation can help with the troubleshooting process when any vibrating machine body part's contact with other parts. The source can be from aerodynamic, mechanical, or electrical sources. If the problem is that the vibrating body part is the direct source of any unnecessary or annoying noise, the problem position is relatively easy to locate. In some cases the body part may cause small vibrations only with no harm done, but if the source is in contact with other parts, the vibration might cumulate to the point of resonance to a very different place in the system while the real source escaping notice. The issue is usually noticed through noise, quantified as either the audible range of cycle and frequency, pitch, or intensity. In most vehicle applications, the intensity of noise is measured in decibels from inside the cabin, but also as external noise from the spectator view. (Volkswagen 2005) Most used simulation method for NVH analysis is to use a multi-body model or vibro-acoustic FEA.

Resonance is a common problem in any vehicle system. Resonance is the tendency for system parts to respond a force through oscillation within the same natural frequency. All objects and parts have a natural frequency, but the exact point depends on material types and geometries. Resonance usually causes noise, which can be classified as either droning, beat, road noise, or brake squeal. (Volkswagen 2005) In tractor applications, the transmission causes usually the highest noise, when a large amount of force goes from the engine through many mechanical gears and shafts, finally releasing the energy to the road or gravel through the tires and/or PTO (power take out). The NVH phenomena in transmission can be analyzed to derive from for example (Rahnejat et.al. 2014):

- Gear rattle, occurring at low teeth impact forces
- Engine order, occurring from torsional vibrations
- Driveline shuffle, occurring from a rapid throttle tip-in and back-out
- Clutch vibration or "whoop", occurring during the clutch transition state
- Clutch take-up judder, occurring when the pull away gear is selected and clutch operated

3.6.6 Collision detection (kinematics review)

A CAD program can be used to perform an interference analysis, to find collisions between different components and other geometries. An interference can occur when different parts or subsystems occupy the same coordinates in the three-dimensional geometric space (example in Figure 15, where a collision is found and then repaired), meaning they do not fit in the same space. Interference problems are very common during the design integration of a complex product with engineers that may not even know each other, which can include thousands of parts that can potentially interfere in 3D space. Interference analysis together differ from FEM and CFD, since it is not a problem of function, but rather a problem of fit. The answer to the problem is also simpler, being either a YES or NO, compared to for example CFD with a more complex solution or answer. (Thomke 2000)

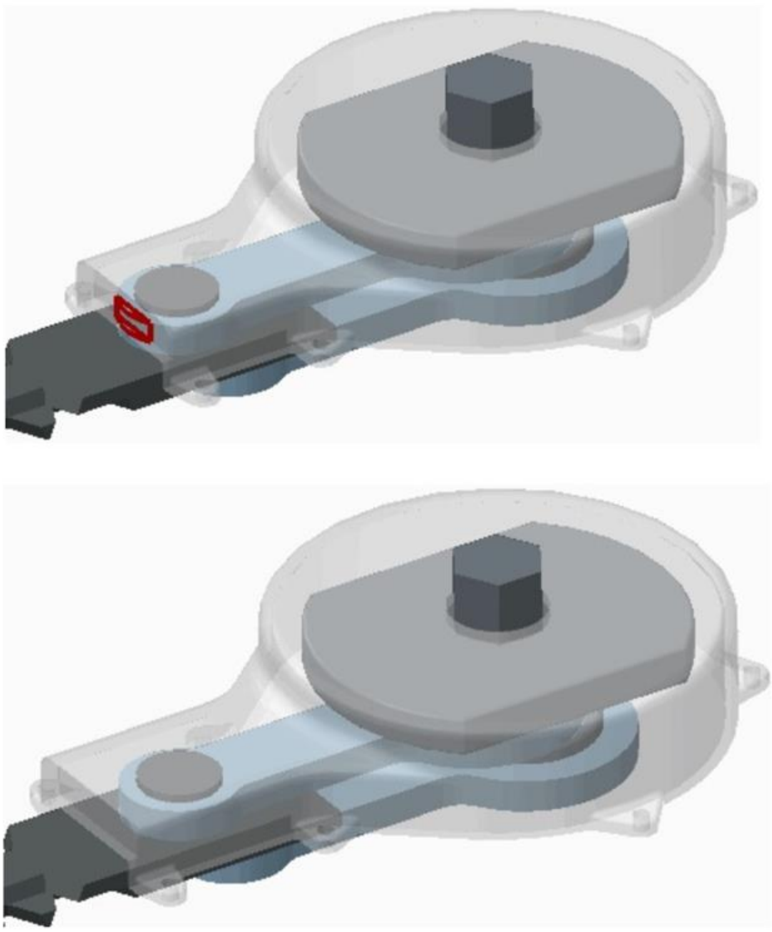

Figure 15: Interferences between components found with an interference analysis in Creo Parametric (found interference on top, and solved assembly below)

Chrysler Corporation, during the development of the 1993 Concorde and Dodge intrepid models, used more than three weeks to fit the powertrain and exhaust systems into the upper body of the car. By contrast, with an early use of mock-ups for decking on their 1998 Concorde and Intrepid models allowed Chrysler engineers to simulate the process and to identify and solve a number of interference problems. This process helped to manage the initial physical fit of the same modules in 15 minutes, that earlier took more than three weeks. By combining new technology with a different development process, Chrysler was able to front-load problem-solving and identify and solve problems at a reduced time and cost. These interface also created a stronger interaction between different design engineers, with the need to solve the issues and problems together. (Thomke 2000)

3.6.7 Virtual assembly

For companies to have a more efficient assembly system to increase profitability and competitiveness with their products, assembly simulation, planning and assessment in a CAD model virtual environment can be utilized. The virtual environment (VE) can be used for identifying potential problems before launching a real factory process and without using physical mockups. This can shorten the design cycle and improve product quality. Furthermore, factory assembly training can be conducted through a VE assembly simulation to train and improve the skills of assembly workers. As an example of using simulation and addressing assembly issues already in the design phase, Toyota shortened their lead time by 33%, reduced design variations by 33%, and reduced the PD costs by 50%. Toyota was also one of the first to users to utilize virtual assembly with V-comm (Visual and Virtual Communication) in the 21st century, mainly used in communication of different factories overseas to get feedback on the designs' assembly routines and efficiency. (Leu, M. C. et.al. 2013)

A virtual assembly simulation in a VE can be used to decide the assembly sequences for new products, to discover interferences or deviations, without the need of building any physical prototypes or assembly tools. (Johansson et.al. 2014) Manikins, as seen in Figure 16 can also be used in the simulation, focusing on the evaluation of ergonomics for the operator or assembler.

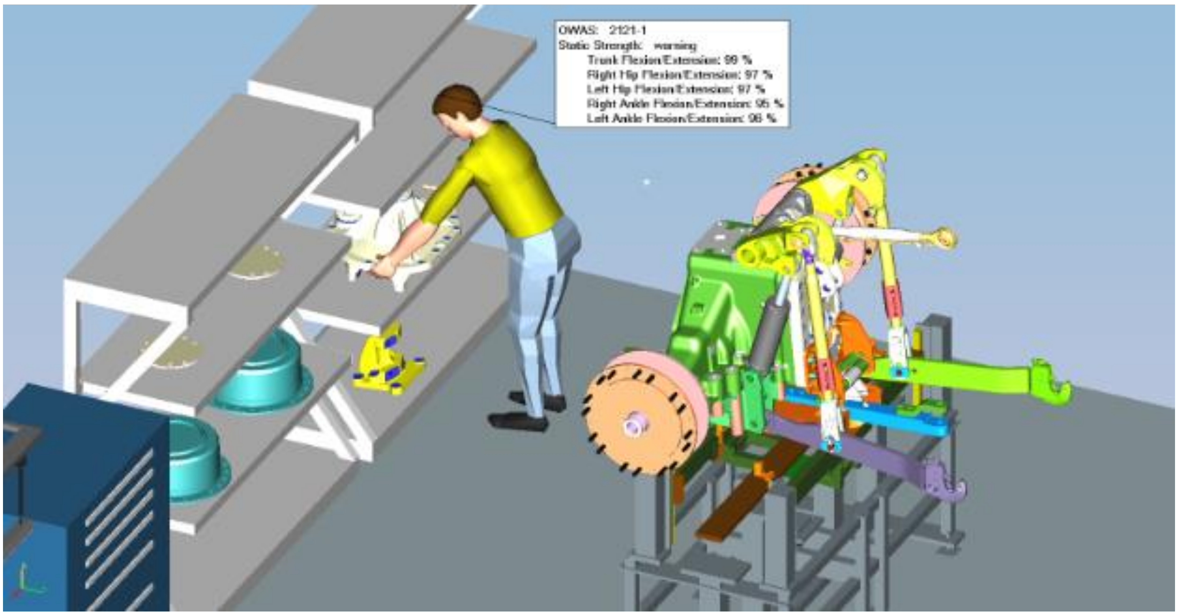

Figure 16: Manikin used in an assembly simulation to analyze ergonomics and assembly sequences (Siemens Tecnomatix Process Simulate software)

3.7 Virtual simulation in a product development process

Due to the new product development constraints of time and cost, engineers often use “carryover” components or systems from a previous model to the next generation. This leads more or less to a conservative design. Physical prototypes also incorporate solutions, which are often already obsolete by the time the prototype is built. So forth, the results of physical experimentation are often not fully relevant in regards to engineering development. “The use of virtual development tools contributes to overcome these (carryover) limitations. In fact, they not only help reduce experimentation costs due to the speeding up of the testing phase, the reduction of the number of costly physical prototypes and redesign linked to their fast obsolescence, they also improve design quality via the availability of information very early on in the development process.” (Becker M.C. et.al. 2005) The use of virtual simulation tools has great potential in product development processes, also with an improved efficiency in obligatory physical tests after reviewing virtual results first, since there most probably will be less chance of having to repeat the tests over and over again.

Kortelainen et.al. (2015) presents the development progress for the evolution of simulation application to the PD process, including four phases that are illustrated also in Figure 17. First, modelling and simulation are used in the PD process in order to solve problems in some engineering details, but the product development is done following traditional design methodologies. The second phase introduces the modelling and simulation of the whole product or large sub-systems with virtual prototypes. This phase increases requirements of the technology used in simulation, but the design drivers are still other than computational methods. The third phase (simulation-based product development) mimics the modelling and simulation technology of the second phase, but with an enhanced simulation-based process approach. Here, the product is first modelled and simulated through coarse models, which produces information for a re-design. This approach requires vast changes in the process, being more difficult to implement into the PD process. With the fourth phase, simulation-based product process is implemented into the management of the whole product life-cycle, with an addition of applying an estimation of environment and selected business models to influence the design decisions. (Kortelainen, J. et.al. 2015)

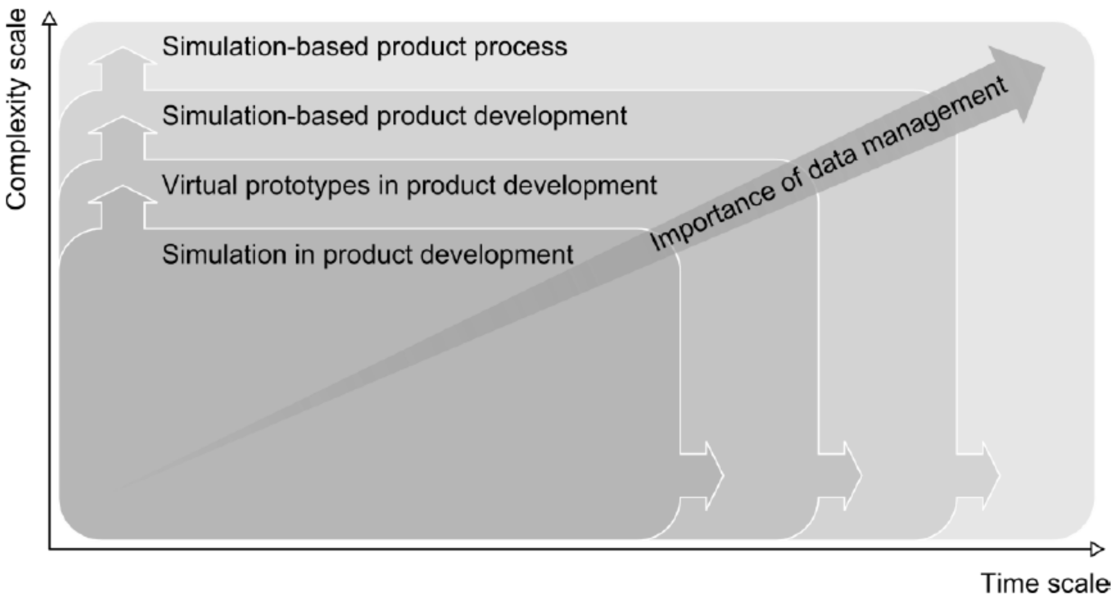

Figure 17: Evolution of simulation application in the PD process with data management importance (Kortelainen, J. et.al. 2015)

In the development of a simulation model, model verification and validation are highly critical, since there are not sets of specific tests that can easily be applied for a detailed or even a general correctness of a simulation or design model. Every simulation project presents a new and unique challenge to the model development team, as there are no algorithms to determine what techniques or procedures could be used in the specific case. Although, some simulation models can be developed for repeated use during iterations and even between projects for carry-over content. In such cases, a system of validity verification needs to be included in the process, for example in a situation where no data is available on the system when a simulation model was first developed, a revalidation of the model should take place prior to new data or system understanding. (Sargent R. G. 2007.)

Connecting optimization methods to the simulators can enable an efficient way of using all the available computational resources. This can lead to success and superior position in the markets, due to better understanding of the product life-cycle aspects, more efficient utilization of resources, and shortened time-to-market in product development. (Kortelainen, J. et.al 2015)

3.7.1 Simulation Driven Product Development

In Simulation Driven Product Development (SDPD), simulations are the basis for the entire product development process. It can include any virtual testing or virtual assembly, and does not limit decisions only related to the design phase of a PD. Physical testing usually is still necessary, to verify legal requirements or to compare the results with real product performance. In SDPD, physical testing is considered as a support function to virtual testing. SDPD can include for instance different virtual simulations, virtual assemblies production-wise, or other 3D reviews of the models generated. Simulation usage in the early phases of a PD process can reduce time-to-market schedules and promote Fast-Fail methodology. (Adams, V. 2006)

3.7.2 Simulation Driven Design

In Simulation Driven Design (SDD), iterative simulation is the basic prospect when generating a new design or an initial concept choice. It is a design process with decisions based on the behavior and performance are significantly supported by virtual design and simulation. SDD can help to widen the criteria of specifications for a new product, with new design modification and verification of any properties. Designers can ask further “what if” questions to evaluate different design options for new innovations. SDD relies still largely on and is complementary to physical testing, being the primary way of verifying a design solution for the product. (Tatipala S. et.al. 2017)

4 RESULTS

This chapter includes the study specific results, from surveys and discussion, and also comprised ideas and descriptions of current state of simulation usage at the Valtra R&D department. Results from the surveys include both present, and future elements to discuss of in the analysis and discussion section. The results are the second main source of information towards the conclusions and follow-up suggestions, besides the more theoretical part of the work.

4.1 Survey and discussions

Engineers within different module engineering areas have taken part in a qualitative survey study at Valtra R&D Department in order to investigate the status of using simulation tools and processes in the company. The survey for design experts was delivered to a total of 36 individuals at different design groups, current product management (CPM) group, and product lines and platforms (PL&P). The survey for simulation experts was delivered to a total of 14 individuals at the simulation group, validation and homologation group, and research and advanced engineering (R&AE) group. The study includes a total of 25 survey responses, with a total answer rate of 50%, and the questions are available in Appendices I and II. Finally, 17 individuals from those that answered the survey, took part in the discussions contributing to the understanding of the current state.

4.1.1 Collaboration of Simulation and Design engineers

The design engineers of each module at Valtra has almost full responsibility of his/her area of expertise. The responsibility usually includes either modules or groups of components, processes, projects, and/or testing. The design engineers’ responsibility is usually to take initiative if simulation is needed with the help of the CFD or FEA engineers. The simulation and advanced engineering department work as a supportive function regarding simulation, mostly giving advice about strengths, air or fluid flows, and structure or system dynamics. The contact between groups and engineers of design and simulation usually starts with a dialog either via e-mail or through face-to-face meetings about what should be studied and achieved.

Although no official or formal documents are written or stored from the process, the simulation engineer can create a specific document for the discussed case to study, and for the requesting engineer to answer in more detail. Besides the unofficial document, there is no common way or process used at Valtra inside the Engineering department. The details contain information about involved modules or components, questions or areas to investigate, project specific details, possible problems expected with the design, and iterative ideas to be compared. A few engineers have standardized the simulations and their collaboration with the simulation team. Others would like to have one but do not have the time allocated to have a process created. About half of the module specific groups do not yet have any experience from simulation collaboration because they have not had or have not recognized the need for it yet.

Because of the lack of simulation related calculation and analysis process, and with no design engineer list of open points regarding design verification with simulation, it is up to the design engineer to initiate the simulation within the project schedule. A simulation job varies in time greatly depending on the component, module, or system to be tested, from a couple hours to several weeks. The results of a long lead time, weeks to months, simulation usually stem from little or no pre-description or model of the task, so the simulation engineer has to start basically from the very beginning. A fairly familiar component, module or system can be simulated in a few hours to a couple days, but as an average the simulation takes a couple weeks. This includes the pre-discussion of the problem, any meetings, modeling, calculation, iterations, and the final analysis. A system wide simulation calculation can take even days, so a good description for the problem is needed to efficiently iterate the system simulation. A component, or module simulation is faster to iterate, with simulation calculations lasting only a few hours. Usually these kind of lighter simulations are left to calculate during the night, so the results can be reviewed in the morning when the simulation engineer arrives to work. If asked from the simulation engineer, it is more preferred to do a more detailed calculation that lasts longer, than several simulations that give less detailed information about the problem. The performance of clusters and computers has improved highly during the last decade, so overall the calculation time has shortened, even though the simulation process nowadays is more detailed and require very high end calculation performance.

4.1.2 The respondent's thoughts on the current state of simulation

Almost every engineer that answered the survey, informed that simulation should be used more in the PD process. Only one (Figure 18) said that FEA and CFD is already being used enough to support the engineering of the design in the respondents area of responsibility.

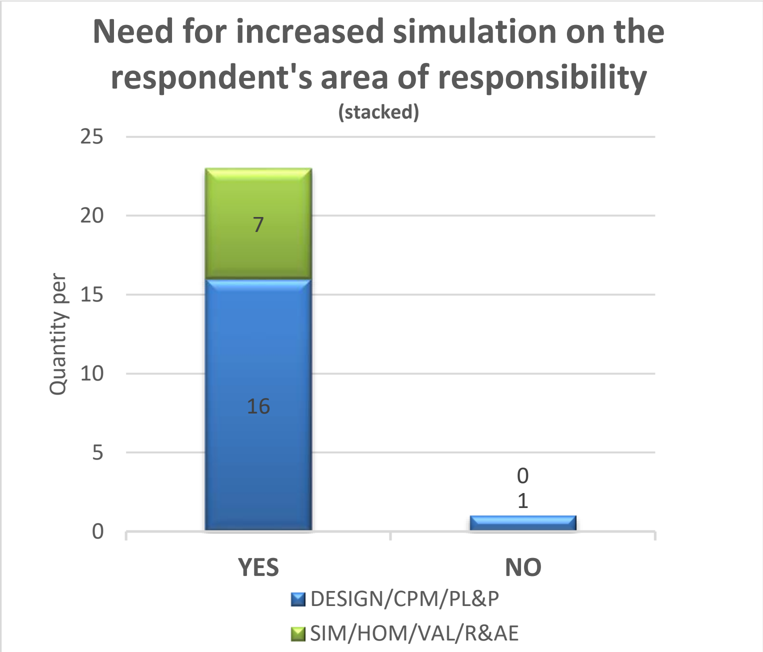

Figure 18: The survey results on the question, "Do you feel the need to increase simulation in your area of responsibility?"

The following are the main points of the thoughts of design and simulation teams on the state of simulation in the company, with comments if there is already a need for increased simulation on the respondent's area of responsibility:

- The cabin design team's most critical part regarding safety, the cabin frame requires the ROPS test after every design round before market release. There however is not a working ROPS simulation model that the test could be done with virtually, so the pre-ROPS test must always be done during the design phase with first frame prototypes to prevent any homologation issues during series release.
- With the pulling equipment and three-point linkages, homologation of these systems is needed when new tractor models are introduced. Sometimes pull systems and linkages have been simulated, but not pre-emptively.
- During the prototype manufacturing phase, it can occur that if the prototypes are too low in maturity, no testing can be done and the project will be delayed, or rushed into

series phase with high risk. Simulation should be used to assess these risk points in the early phases of the project.

- Transmission related oil flow duct pressure losses, lubrication balance estimation, and hydraulic circuit power should be taken into account with simulation, if only indicatively. Also the dynamic behavior of the transmission, its masses, temperatures, and lubrication should be taken into account.
- Projects are not mature enough and too much of content is shared again after a pre-series production is made. This mostly is the effect of short time-schedules and the use of external design work.
- Cables for hydraulic blocks should be analyzed with kinematic simulation to prevent low performance issues. Also early reviews for tire space reservations should be done with kinematic solutions, alongside any cabin or hood related space issues.
- The cooling flow characteristics, HVAC (heating, ventilation, and air conditioning), air intake, exhaust temperatures and flows are usually tackled with too large safety factors due to hasty design solutions.
- Reduction of design iterations through simulation should be promoted. This way the time to market could be shorter. Many problems risen from prototypes could be discovered and solved already on the design table if simulation had more time and resources.
- The analysis of noise issues and resonances should be increased, because the correction of these problems from the final structure is really challenging
- Simulating, for example, the strength of the plastic parts to be made by injection molding during design could optimize the amount of plastic material in the part, thereby achieving significant cost savings. By simulating the filling of the molds of injection molding parts, the position of the feed point could be determined in advance.
- Simulation should be keener on supporting conceptualization and problem solving.
- At the moment, the tools are not being utilized as well as they should, e.g. compared to the situation 5 years ago, and partly also the skills with both the simulations themselves and their utilization in the design process have become obsolete.
- Simulations could be done more precisely but more workforce is needed. In addition, the construction of various models, and validation itself would make sense. Now it

seems that simulations do not have time to validate properly in reality, only comparing simulations with each other makes sense with the time available.

- The potential of simulation is currently not exploited. At the moment, it is possible to simulate what is possible with these resources, but it would be possible to use the simulation much more widely if more resources were available. Simulation should be exploited at an earlier stage of the product development process. At present, a rather large part of the simulation resources goes into solving the identified problems. Many of these problems are such that the simulation could have reacted to the problem even before the prototype validation phase.
- Projects are in danger whenever we develop something new. When we make a few prototypes that break, we are far behind the project budget.
- Simulation before and during design gives a really good view of how the product will meet your set goals. Verification and validation, especially in case of problems, simulation can play a major role in the end result defined at the end of the process.
- For example, when designing all kinds of brackets, it would be good to use the simple strength calculation to map the tension and bending of the different options. The quality of the design would improve, less repairs and prototyping. This could be done by the designer himself or by someone with a light strength computation ability whom could ask for a review. Higher risk cases of course for simulation team.
- The use of multi-part dynamics in computation is rather limited. The models are old and engineers do not work with them on a continuous basis. In general, the lack of initial data for FEA is a major challenge in strength calculation.
- Determining and taking into account real-life loads at an early stage of the product development process requires the use of functional multi-particle dynamics models and continuous development.
- According to one definition, the task of product development is to generate new knowledge, and learning speed reflects success in the task. The more immediate the feedback received by the designer from the simulation is, the faster the results can be learned. The earlier the problems are detected, the better the time to react (without stretching the project schedule). The current practice is, unfortunately, often that parts are already in production at the time they are still simulated. Obviously, remedying the shortcomings identified at this late stage is always costly.

- Designers could perhaps simulate more when designing parts so that the parts are more ready when the actual strength calculator is taken into consideration for the part or assembly. For example, simple static simulation could detect stress concentrations that would probably cause problems with a dynamic load.
- In general, simulation is a sensible investment in product development, as it can make an early analysis of a project that can detect potential problems and change / improve design. And this can also be done relatively cheaply compared to traditional "prototyping and testing". At an earlier stage, such designing potential risk spots are discovered and are possible to change, so they are cheaper and easier to modify in the project or the final serial product.
- In the future, system level analysis and simulation of dynamic phenomena could be developed / enhanced. Better knowledge of vehicle dynamics development of features, avoiding problems. Transmissions / power take-offs will soon be facing big changes.

4.1.3 Methods of ordering simulation from the simulation team

The methods to order simulation in the Valtra R&D department are usually a face-to-face conversation regarding the problem at hand, or an e-mail that is sent with the preliminary information. Some use both methods. About half of the engineers that answered the survey have not had any tasks yet with the simulation team (see Figure 19). Sometimes the simulation engineer creates a document for the task according to the research question at hand, and does an iterative round with the design engineer to verify that the correct questions are under inspection with the simulation. One particular comment was worth mentioning regarding the simulation orders: “It would be good to talk more about this. Ordering simulation work should be done so that the subscriber knows what he is ordering and what he wants from the simulation, but on the other hand ordering should not be too heavy.”

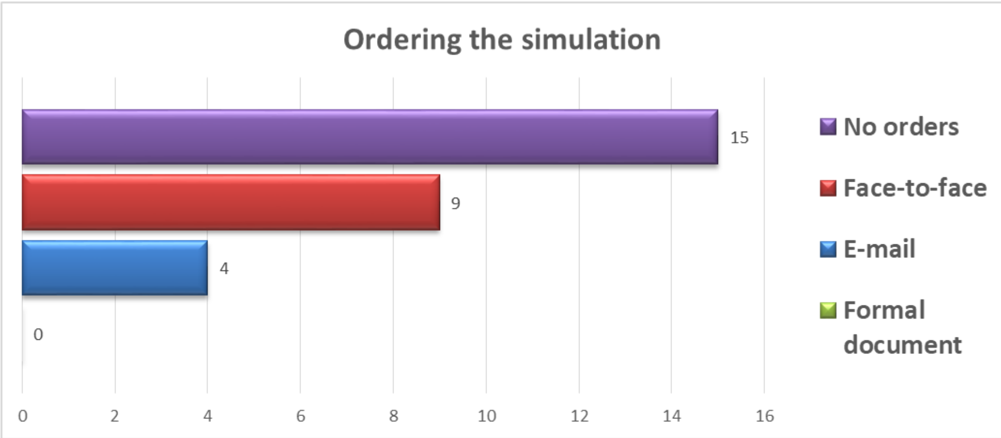

Figure 19: The main simulation order methods used in the R&D department, according to survey results.

4.1.4 Simulation reliability verification methods used

According to survey answers, some simulation results verification methods are already in use, for example:

- Loads and conditions are carefully selected
- Validated with a real physical test
- Simplification of models
- Discussions about the starting situation and the goal
- Refining the source data
- Iteration cycles
- Communication and documentation
- Criticism of the results
- Trust in professionalism
- Asking again what was wanted to research for in the beginning
- Order form conducted on which the plan is based

Also, many additional methods for confirmation were proposed for future improvements:

- More value for refining the problem source data
- At least three iterations per problem
- Simulation model verification process
- Simple simulations performed also on the designers table

- Standard forms that require certain input/output data
- Feedback from previous project results
- Continuous comparison to physical tests

4.1.5 General trust to simulation results

As part of the survey, the engineers from both design and simulation teams responded to answer a question about how confident they are towards the simulation results they get. The scale was according to Appendix III, and the respondents could choose several options, not only one level of capability. In Figure 20, the results are illustrated with stacked lines. Highest amount of votes was given to level 4, with a “Simulation is predictive, though validation testing is required” description. Second most votes was given to level 3, “Simulation is predictive, but requires physical testing to calibrate models”.

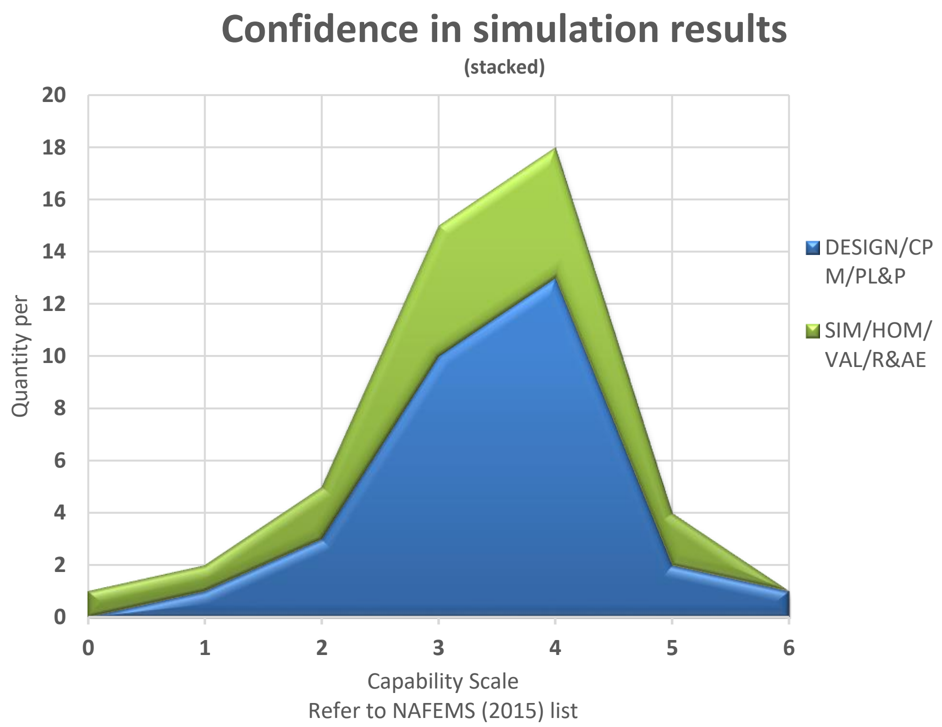

Figure 20: Confidence in simulation results

4.1.6 Known obstacles in further implementation of simulation

One of the questions in the survey was to inquire what kind of obstacles does the design teams recognize for further implementation of simulation in their work. Answers included for example the following:

- Changing species and situations throughout the project
- The designer doesn't have time to familiarize himself with simulation
- Confirming the conditions of the problem are challenging
- Tight design schedules
- Resources are limited
- Extensive parameter measurements
- Reaction time for simulation needs are slow, Fail Fast ideology does not work
- No needed software or calculation tools are available
- Time consuming and heavy simulations
- Incomplete initial condition data
- Ashamed to ask help from simulation team to simple problems
- Sometimes even impossible simulations
- Aging of simulation models
- Too complicated software for kinematic simulations

4.1.7 Simulations executed by the Design Engineer

The design teams normally use Creo as the preferred tool of virtual 3D modeling. Several engineers that use Creo as the primary tool, emphasize that Creo Simulation tools should be more used to see differences when comparing different designs together. CATIA is a more popular software among design engineers with more experience in the company, since Creo has been introduced later. The simulation engineers emphasize the fact that the Creo tools should not be used to find any absolute values, but rather comparisons between designs. The more capable FEA software like ANSYS take more time with the simulations, being more precise in configurations, but with a faster tool right at the design engineer’s table, the iterations are much faster to produce, with lots of data from the performance and usability of parts or modules before one is actually even built. This promotes to have designs ready and tested before the usual deadlines. The quality of design improves, and the PD process is even more efficient with huge amounts of system-wide weakness and strength knowledge of the design way before any prototypes are even built.

4.1.8 General thoughts about simulation in PD

According to the survey results, simulation is already used quite well but only occasionally throughout the PD process, from concept phase to series production. Some said that simulation is already used in verifying the first specification of a new design, but others said that simulation is always brought into the design phase too late. In some cases, simulation is done by the supplier of said system or module, but mostly the system simulations are done by the end product design teams. For example, CFD simulations for air intake are considered to be done during the first phases of the project, but for the EAT (exhaust after treatment) systems the simulations are done too late in the project. Homologation type approval related issues, for example field-of-view reviews and visibility angles are inspected already in the first phases of the PD in 3D. The approval tests for cabin safety are done very late in the project, which means early FEM simulation for cabin frames should be considered highly.

4.2 Plausible simulation targets

As per the results of the survey and discussions, some critical or new design related non-simulated systems were discovered:

- Cabin frame, even small changes require repeated tests, and they are expensive to arrange with frame and transmission purchasing and official test labs. The ROPS test has already been performed in the past, but due to an aged simulation model, the simulation of ROPS is impossible for the time being. An update to the model is required to be able to perform FEA calculations for the cabin frame.
- LAT (limiting ambient temperature) laboratory test runs are performed lots of times, consuming testing resources. Simulation correlation with CFD should be researched for to allow simulation usage in replacing LAT test runs.
- Laboratory tests for transmission multi-disc clutches are very time consuming. They could be performed through CFD and FEA simulations if resources would be transferred to computational testing.
- HVAC tests are troublesome because of the limited performance specifications for cost-efficiency. More optimization could be done through iterative CFD calculations.

- Pulling equipment and linkages are costly to perform in supplier and official test laboratories, this could be well managed by FEA simulations to minimize the need for physical testing.
- Transmission endurance tests could be performed with FEA, to reduce the need for occupying test laboratory for long duration endurance tests. FEA also allows the analysis to find the weakest points and not breaking any physical components.
- EAT line thermal and vibratory issues could be prevented early on in the project with CFD and NVH. FEA could be used also to prevent any structural issues with brackets and flex elements.
- Any noise and vibration related issues for driver comfort and part durability could be discovered even before building the first prototypes of tractors. When noise issues are found in the field tests, usually no big changes can be made within the PD process schedule.

5 ANALYSIS AND DISCUSSION

In this chapter, the results are analyzed and discussed in parallel to the theorems of simulation methods, PD processes, and risk and data management.

5.1 Simulations in the Product Development Process

When simulations are introduced in the PD-process with a tight time schedule, they are usually made in parallel with ordering physical prototypes, leading to simulation results being useless for a re-design before actual physical prototype testing. The lack of contribution for virtual simulation in the PD process primarily leads to that it is up to the design engineer to take the initiative of involving simulation in the project. Secondarily it leads to the need for a prescribed description and engineers' check list of simulation cases and their analysis. Therefore, when simulations are performed during a project, the process phase for the involvement of simulation varies highly from occasional concept studies to not being included until later just before the end of the project when design has already been locked from changes. Traditionally simulation has entered the project too late, when the reliability of modules and/or components have already been tested in the field or with physical laboratory tests and deemed inefficient or bad for customer use. Most likely the drawings and designs have been locked and only small or no changes can be made.

Even now, no clear documentation or instructions exist on how and where simulation work should be done during the PD process. Physical testing is well documented and enhanced through risk management in all the phases of the PD, with gate approvals for critical system-wise testing. Physical test vehicles and separate test modules require much planning and administrative work, with huge costs, which can sometimes direct the whole PD schedules and plans entirely for the rest of the project. Physical tests have a clear path and stages, but virtual simulation does not have any milestones within the projects of Valtra. Additionally, PDM systems do not fully yet support simulation, and this can have a big impact with new design simulation incentives of design engineers. All the design and test data are in the PDM system, but if simulation data is not complimentary to the system, no easy or simple way of doing comparisons between data is possible.

When prioritizing is needed within a projects time schedule, prototypes for physical testing are most of the time focused on, rather than managing simulation for design validation. The physical prototypes tend to have clear deadlines, and simulation is not usually even included in a projects design process requirements. Simulations are mostly also not included in the DVP lists, but are occasionally considered in the DFMEA calculations as their follow-ups. At the moment the demands regarding simulation and other calculations in the PD process is absent. A simulation job is usually ordered because of the interest for simulation from the design engineer, or to reiterate a problem that has already been discovered through prototype testing. The design engineer usually has some interest towards simulation also from the historic point of view, if enough experience has been cumulated towards a similar design. Furthermore, project management should include and give support for simulation loops more in the PD process. This would also have an impact on the designs to be more accurate before uploading them into the PDM system, while having more information overall from the design performance.

Today at Valtra, design engineer can do some FEM simulation by themselves in Creo Simulation. This is helpful when implemented into weekly work load, so simulation iterations are increased while not increasing or over-cumbering the simulation engineer team. In this case, the simulation engineer can rather act as a support factor or a review counsel to help improve and evaluate and compare the results from the design engineers' simulations. However, this kind of work is done only a fracture of the time that could be possible, since the Creo Simulation tool is only used if found enough interesting by the individual design engineer. The start of simulation iteration needs time the first time, since the design engineer needs to first learn the basics of the tool and the simulation process. This is not usually possible from the aspect of time and project schedules.

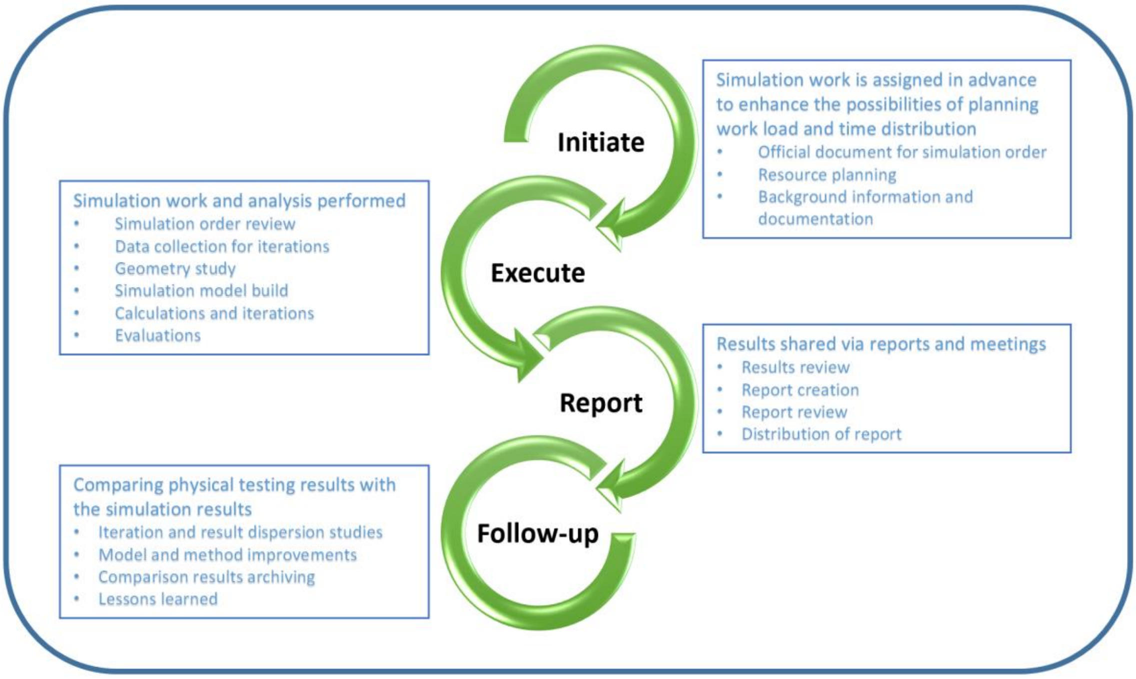

Figure 21: Work process suggestion for simulation

In Figure 21, a process is described comprising of four different phases:

- Initiate
- Execute
- Report
- Follow-up

Simulation assignments are usually made through iterations in collaboration with the design engineer and the simulation engineer. The iterations of the simulation work usually takes place in the Execute phase, but sometimes between the Execute and Report phases for a more detailed and controlled process. At least three iterations should be done as a standard protocol, before the design engineer can reliably trust in the simulation results and outcomes, and requirements for the design can be met. Because of the simulation and design iterations, one single simulation work can comprise from more than one loop of calculations. However, if a long time gap has occurred between the iterations, it is suggested that a new simulation order is made instead and the old one is concluded through Follow-up phase.

5.2 Virtual simulation impact on Product Development process

As described in chapter 3.2, the AGCO AMPIP gate process for NPI projects has six phases. Because no preconditions for virtual simulation are yet assigned, a proposal according to different areas of simulation and for the sake of PD process integrity is presented in Figure 22. The incentives for simulation gate deliverables are described next.

5.2.1 Concept Review gate

The CR gate includes the reviews for all simulation objectives and targets regarding the content of the project. At the gate the approval question asks, are all the concept simulations defined, so a proper review for new design performance can be initially evaluated system-wise before the project approval. The CR gate also includes the review for previous project simulation comparison report, so any project performance issues regarding simulation can be assessed.

5.2.2 Project Approval gate

The PA gate asks, whether all the concept simulations are done. This should be a pre-condition for any new design development, so data is available about the feasibility of the new content. The risk management should be performed already at this gate, so a DVP list has been defined for the design phase simulations. Also any simulation related validation goals should be defined for the gate approval.

5.2.3 Design Release Gate

To pass the DR gate, the project should have a simulation related question of whether the critical and new design simulations are performed and passed. The DR gate is usually the longest in regards of time, so multiple iteration rounds should be performed during this phase. It is also where most of the simulation related DVP tests should be performed.

5.2.4 OK to Produce gate

The OP gate approval should ask, whether all the DVP simulations are finished, and if they are validated. This is the second most time consuming phase, in which the full system validation of the new design content is performed. All tests and simulations should be finished, and validated for gate approval.

5.2.5 OK to Ship gate

The OS gate includes all the implementation related tasks, so for simulation related gate approval all the residual design risks should be accounted for before the approval. This is the most critical point in the PD process, when all the project risks are accounted for in regards of the final customer. From the earlier gates, review should be made for all the performed tests and assess any residual risks that can derive from product use conditions that are not yet simulated.

5.2.6 Project Performance gate

The PP gate is possibly the most important gate regarding future projects of the same kind. The follow-up of simulation results and comparison to real field data and customer feedback should be reviewed here, and an approval question for the gate should ask if the data comparisons and a conclusion report is made. This comparison report is then used in the next project's CR gate to review any issues with simulation performance and physical test data, so improvements can be made to the simulation calculations and their iteration rounds.

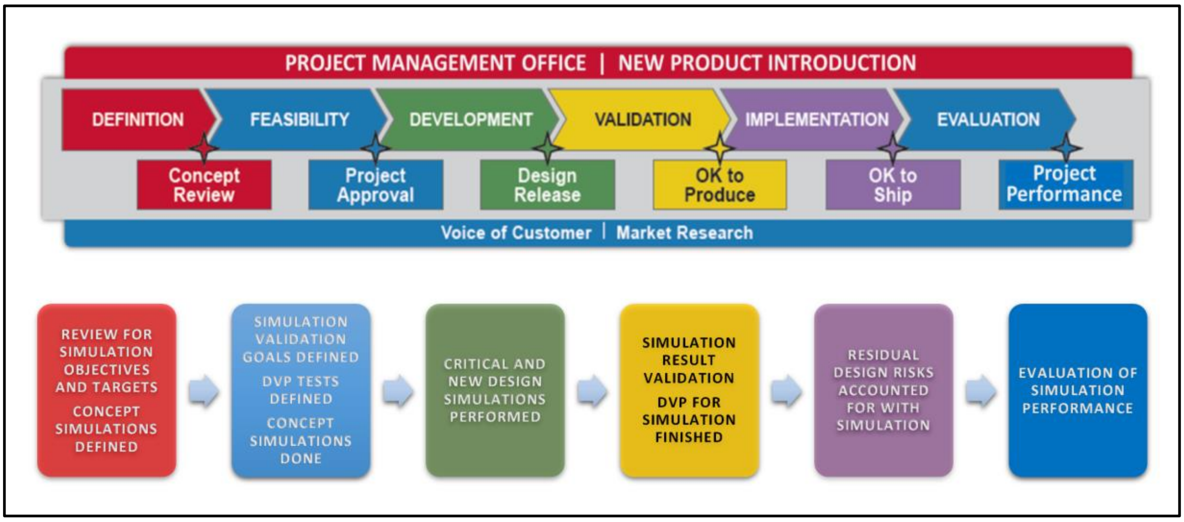

Figure 22: Suggested simulation implementation to AMPIP gate process, with AMPIP on top and simulation objectives below

5.3 Design risk management impact on virtual simulation

Design risk management has been researched for in good quantities, and multiple different tools have been designed for an efficient way to assess design risks in new products and processes. If virtual simulation is further implemented into the risk analysis as a proactive measure or as individual tests into the DVP, a number of physical tests could be cancelled and/or replaced by simulation. In some cases, only one physical validation test might be required, when comparing the results to previous test data with new design risk analysis. Simulation test cases can be first discussed when making risk mitigation plans for risk assessments, and further taken into account during the residual risk analysis of a risk management process.

5.4 Confidence in simulation results

As Figure 20 depicted, most engineers at Valtra tend to think that simulation can be used as a predictive measure to compare and assess designs, but most of the times validation tests and physical measurements should be done. Calibration of models through physical testing is also needed. If the simulation results do not match the physical testing results, engineers tend to question the simulation more than the physical test arrangements, even though each iterative physical measurement would show very different results. Simulation is used as a problems solving tool in some cases, in which the source of the problem can be identified. This kind of work boasts the confidence in simulation, and should be highly promoted. Further implementation of simulation into different areas of tractor PD in the organization would stem new ideas for pre-emptive design analysis. Any suspicions towards new work on simulation is a blocking point for further SDPD implementation.

If the design relies too much on physical tests, it can be dangerous for the quality of end customer use of the product. One broken component in a series of long duration physical tests without proper analysis can lead to a huge amount of wasted time and effort. This is why one physical test should not overcome the results of iterative simulation calculations. The supportive tendency of both test aspects should be used co-operatively, so the results are compared and analyzed together. This way more detailed conclusions can be drawn when trying to find the source of the problem. Confidence towards simulation methods is a key factor in implementing SDPD into the PD process.

5.5 Answers to the research questions

Here the research questions are answered, and further summarized in chapter 6.

How much and what parts of the tractor's product development and testing could be simulated?

The main modules are listed here, with few examples of the possible simulation targets. A map of the module view and simulation methods related in the Appendix XI. Practically all the main physical modules and systems of a tractor can be simulated, the constraint for a wider implementation being the reallocation of resources.

Cabin
- FEA
  - Cabin frame tests
- MBS
  - Cabin suspension and seat ergonomics simulation
- CFD
  - Air conditioning and aerodynamics
- Kinematics
  - Operator equipment and freedom of movement
- NVH
  - Noise and resonance issues
- VE
  - Mirrors, lights, i.e. operator related freedom of vision constraints

Linkages and pulling equipment
- FEA
  - Integrity and dynamic tests
- Kinematics
  - Trajectory and collision detection of hydraulic lines and linkages

- Engine installation
  - FEA
    - Brackets, castings, flexible parts
  - CFD
    - Exhaust, air intake, cooling capacity, thermals
  - NVH
    - Engine and EAT noises and resonances
  - Kinematics
    - Hood freedom of movement, engine part collisions
- Transmission
  - FEA
    - Integrity and durability
  - CFD
    - Hydraulics and transmission lubrication
  - NVH
    - Noise and resonance issues
  - Kinematics
    - Hydraulic lines, rotators and switches freedom of movement
- Transaxles
  - MBS
    - Suspension simulation
  - FEA
    - Axle integrity and durability
  - Kinematics
    - Tire spacing and freedom of movement

Are there proven issues in the field with relation to passed validation tests that could be taken into account with simulation?

Transmission related durability issues are most common, with oil leaks and axle breakings. Usually they are issues that the laboratory tests could not reproduce. HVAC tests also cannot physically simulate every different ambient or other use conditions, so usually some issues stem from the customers on the cooling and air conditioning systems. EAT related exhaust purification component poisonings have been found from the field use, with no ability to reproduce in laboratory conditions, but this is uncertain how simulation could be used to assess similar situations. Noise issues are also common, and they stem most of the time from worn-out or loose parts. Transmission related noise can be tackled with simulation. Any vibration tests also for the engine installation modules could be assessed better, since brackets and other supports tend to break in different load conditions that maybe cannot be pre-emptively be tested in laboratory conditions.

What are the most time and cost consuming areas of development that could be assisted with simulation?

Cabin frame related tests, being very critical in terms of safety, but also expensive to arrange with frame and transmission purchasing and official test labs. ROPS testing and other frame integrity related tests should be performed with simulation for pre-emptive measures. All the engine related tests, such as LAT are performed lots of times, consuming testing resources significantly. Simulation correlation to LAT test runs and HVAC tests with CFD should be further researched to allow further resource allocation to simulation and more pre-emptive measurements to be done in the physical testing laboratories. Any endurance tests should also be replaced partially with simulation, to do iterative testing. Only the most certain tests should be done with the physical prototypes for last measures, so the risk of failing in the test bench is minimal. The most used structures during tractor work are the pulling equipment and linkages, and they should also be simulated before any physical testing, to be able to place more trust into the material and geometry selections. All the molds for castings and plastic part material optimizations should be used more, to decrease the materials needed in each part. Thermal, noise, and vibratory issues are the most common with exhaust lines and other engine related modules, CFD and FEA calculations should have more focus in pre-emptively assess the possible issues. These parts are costly and time-consuming to reiterate, so all the issues that can be tackled before design release will be a huge positive impact on performance later on in the project.

How can simulation be integrated into product design, design validation, and design risk management?

The most efficient way of implementing simulation into a PD process, is to raise questions in the gate approvals of each PD phase. The approval or rejection of the gate is reviewed at a high level in most companies that use the gate approval, so any issues with each step in the process are well noticed. Most of all, the validation of simulation results and comparison to physical testing should be raised in high priority. To prefer simulation more as a tool in the design and concept design phases, simulation software implemented in Creo should be taught and instructed more to be implemented into the every-day work of a design engineer. The gate approvals should also include the risk management tools, so the DFMEA and DVP tasks are performed early on in the project before any design release. This would be a pre-emptive method of reducing time waste and amount of rework. The process is explained in chapter 5.2 in more detail. The PDM process is usually a separate function in the PD process, but integrating simulation database into the PDM is essential in keeping the simulation loop intact. See chapter 3.4 for further details.

What applicable simulation methods are not yet in use?

In the company, only the NVH method is not in use. These tests are usually done with physical tests, by measuring any noises and/or vibrations potentially stemming from the tractor transmission and hydraulics. Though it is a reliable way to measure, usually the tests are done too late in the project. Transferring resources to simulation could help in finding these issues before any prototypes are build. Though performed in the past but not present, FEA for ROPS tests should be accounted for in more detail, and the simulation models should be updated more frequently. The update needs months of work at first, but only a fraction of that time annually if the model stays up-to-date.

6 CONCLUSIONS

This chapter includes the study summary answers to the research questions introduced in chapter 1. Follow-up measures are then introduced according to the theorem and results. Finally further studies are proposed, deriving from the areas of interest detected before or during this study and did not have the opportunity to research and discuss.

6.1 Research questions

In this chapter, the research questions are summarized, and can be found in more detail from chapter 5.5.

How much and what parts of the tractor's product development and testing could be simulated?

All the main modules and systems can be virtually simulated and tested with several different methods. The most critical and costly modules that do not yet receive the full potential of simulation support can be further simulated with an increase or reallocation of resources from physical testing and design engineer simulations. Further simulation implementation has the potential to detect design faults and structural challenges early on in the projects.

Are there proven issues in the field with relation to passed validation tests that could be taken into account with simulation?

Several issues are always stemming from the field of end customers and product service. Transmission related durability issues that cannot be reproduced in the laboratory tests. HVAC tests that are hard to test in different ambient or other use conditions. Noise and vibration related issues could be found early on in the project with NVH analysis of different modules. Any structural fatigue or breakage of components produce large issues warranty-wise, and could be checked and pre-emptively calculated with simulation.

What are the most time and cost consuming areas of development that could be assisted with simulation?

- Cabin frame design and integrity evaluation
- Engine related performance, such as LAT
- Any endurance related modules or components, e.g. transmission

- Pulling equipment and linkages, with large impact on the whole system integrity
- All the molds for castings and plastic part material optimizations
- Thermal, noise, and vibratory prevention with design

How can simulation be integrated into product design, design validation, and design risk management?

- Simulation into the PD process as a deliverable, for questions and as a decision making tool
- Implementation to the risk management process to assess risks with simulation
- Comparison to physical test results, and calibration of simulation models accordingly
- Design engineer simulations, with a fast and iterative way to improve design performance
- Implementation of simulation into the PDM systems to further improve assessment of design and test results

What applicable simulation methods are not yet in use?

- NVH method is not yet utilized with virtual simulation
- ROPS FEA simulation not utilized for the time being

6.2 Recommendations for follow-up measures

Derived from the theorems, results, and results analysis of this thesis, follow-up measures are recommended to the R&D functions of Valtra. The recommendations are more specific to the aforementioned company, and perhaps cannot be as widely used in general to other companies on the same field of work.

The threshold of making contact and discussing with a simulation engineer regarding different problems and questions towards a new or old design performance should be lowered. One main key components in this is to apply a newsflash every now and then to design engineers regarding the possibilities of not only with the simulation team, but also what the design engineer can simulate individually. FEA calculations done by the design engineer can have a huge impact on the schedules of design implementations by reducing the time needed. Simulation engineers should support the effort with process review, and training both with individual teaching of FEA and in groups. A support function within the organization should remain close to design engineers.

Every test and a performance mimicking a test should be thoroughly described and defined to properly simulate the test situation at hand. Such a systematic simulation method development would fulfill the testing demands of products that grow more and more complex. To be able to reduce prototypes during a PD project, a simulation process with detailed description of every phase should be formed.

FMEA is usually started already in the concept phase, and should be updated and improved during the whole PD process. This is nominally not the case though, since the FMEA is generally produced during the first steps of the project, and then forgotten about as the project continues. Most of the PD project test cases arise from the DFMEA calculations, and simulation should be considered more of a DVP test case than a supportive function for physical testing. A follow-up on the late phases of the project should also include the review of the DFMEA, and the simulation results responses to related failure modes.

A more simulation and analysis oriented SDPD process should be implemented. At the moment, simulation does not act as a decision-making supportive deliverable from the PD point-of-view. Neither there is any documentation on when nor how simulation and their analysis should be performed. It should be an activity that is scheduled and planned early on in the project description, before any system-stage physical tests are performed. It is desirable to use simulation results as key values when evaluating concepts, and having the analysis of the iterations to be involved in important decisions during the project content review. Virtual simulation has a very short lead time compared to any physical prototype related testing, which maybe also has a schedule shortening effect early on in the PD process, but most importantly during the whole remainder of the PD. It will advance any design activities, instead of post-pone of the whole PD process with physical tests. Iterations can also be multiplied, so the most optimal result is available already when building the first fleet of prototype machinery for field testing, resulting in front-loading of the project work-load. This simulation oriented process should be established, with the involvement of design engineer simulations, and the feedback loop of physical and virtual testing.

6.3 Further studies

During the study, a series of questions were risen in the context of the work. Due to a limited schedule and study limitations of the work, these questions and problems detected are noted in this chapter. However, the points are important for an efficient implementation of simulation into a company's PD process.

- How can a detailed test description be formed if the goal would be to fully replace a mechanical test with a virtual one?
- What would it demand to perform an individual test, which has not yet been performed mechanically, with simulation?
- What would the process be like where simulation is compared to and specified to be reliable enough to replace mechanical tests?
- What kind of a connection can be stablished between levels of simulation and the resources it requires?
- How could interactions between simulation and physical testing groups be complementary functions to each other?
- How can the results from physical testing be used to develop more accurate simulation models if the results from physical testing and virtual testing does not correspond to each other?
- How can system software logic simulation (Matlab, Simulink etc.) performance optimization be integrated into virtual simulation on applicable module tests?
- How can virtual simulation process be implemented into the design related PDM systems, for further data and test results comparison performance?

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Survey questions to the design experts:

1. Do you feel the need to increase simulation to your area of responsibility? Why?
2. How many different systems / modules do you have for your design team responsibility per project?
3. Which systems / modules are critical and are hoped to succeed at once, to save time and cost?
4. Which of the systems / modules you are responsible for are the hardest to test in laboratory conditions?
5. Which tests passed through laboratory tests have caused the most annoyance afterwards, for example in guarantee statistics or in the field?
6. What different systems / modules have been able to test so far by simulation?
7. How do you make sure that the simulation order responds reliably to the original question?
8. Which systems / modules create the biggest cost items during the product development process?
9. In which phase / stages of the product development process do you use simulation?
10. How do you order simulation work from the simulation team?
11. How much on average do you rely on simulation results that you have achieved with the SIM & DES collaboration? (refer to appendix III)
12. Have you found any reason / obstacle that makes it harder to implement simulation further in your area of responsibility?
13. Do you feel the need to add simulation in your area of responsibility? If so, which systems / modules, in particular?
14. Any other thoughts, questions, comments?

Survey questions to the simulation experts:

1. Do you feel the need to increase simulation in the product development process of the company? Why?
2. How many different systems / modules do you have for your simulation team responsibility per project?
3. Which systems / modules are critical and are hoped to succeed at once, to save time and cost?
4. Which of the systems / modules you are responsible for are the hardest to test by virtual simulation?
5. Which tests verified or tested by virtual simulation have caused the most annoyance afterwards, for example in guarantee statistics or in the field?
6. What different systems / modules have been able to test so far by simulation?
7. How do you make sure that the simulation order responds reliably to the original question?
8. Which systems / modules create the biggest cost items during the product development process?
9. In which phase / stages of the product development process do you use simulation?
10. How is simulation work ordered from the simulation team?
11. How much on average do you rely on simulation results that you have achieved with the SIM & DES collaboration? (refer to appendix III)
12. Do you feel the need to increase simulation in your area of responsibility? If so, which systems / modules, in particular?
13. Any other thoughts, questions, comments?

Capability scale for simulation to support engineering decisions:

Level 0: *Simulation has no capability*

Level 1: *Simulation has some capability, but is not useful*

Level 2: *Simulation can be used to sort, but not select, alternative designs*

Level 3: *Simulation is predictive, but requires physical testing to calibrate models*

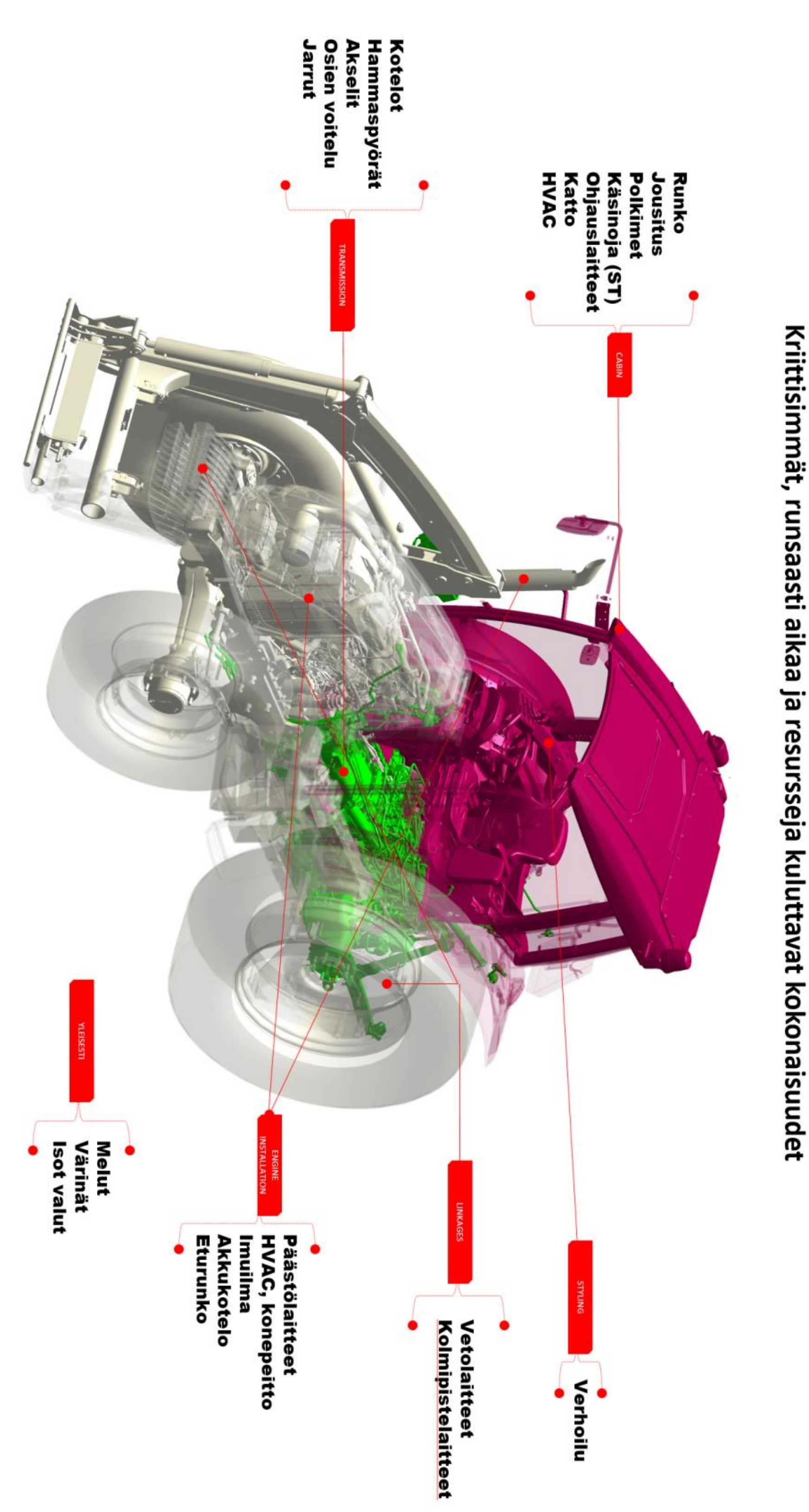
Level 4: *Simulation is predictive, though validation testing is required*

Level 5: *Simulation is predictive, and no validation tests are required*

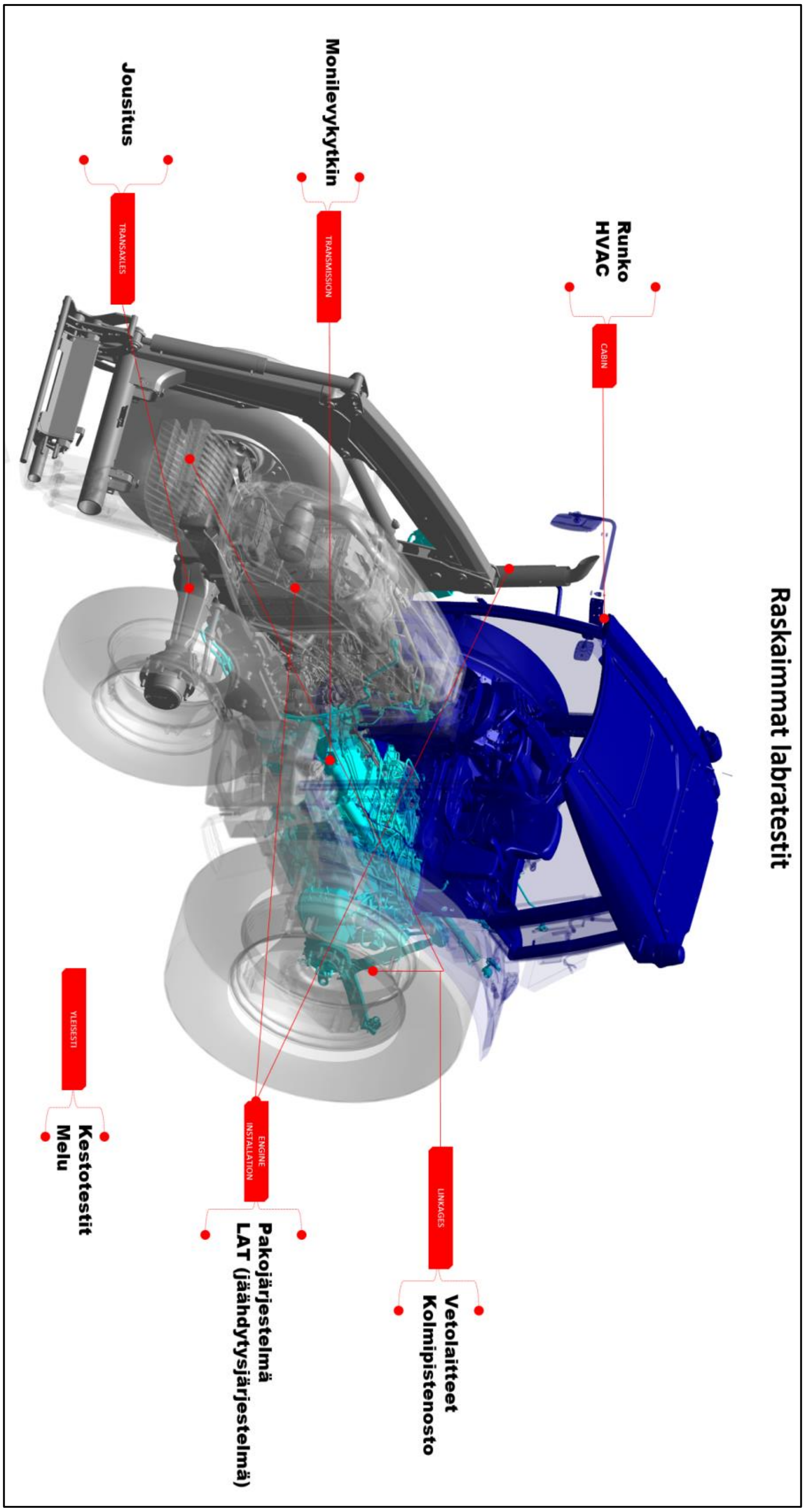
Level 6: *Simulation is more capable than testing and validation*

(NAFEMS Benchmark Magazine 1/2015)

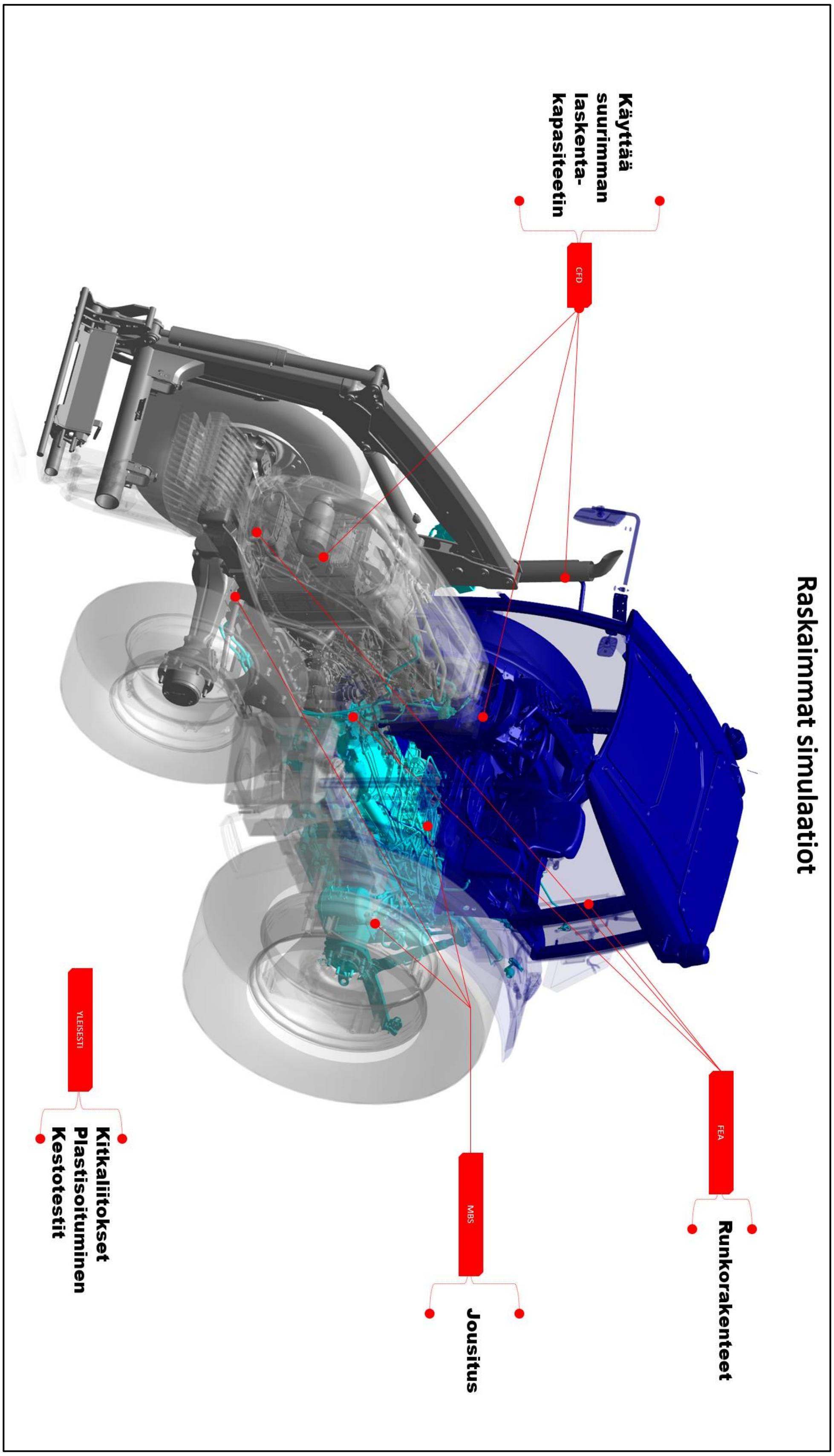
The most critical, lots of time and resources consuming systems



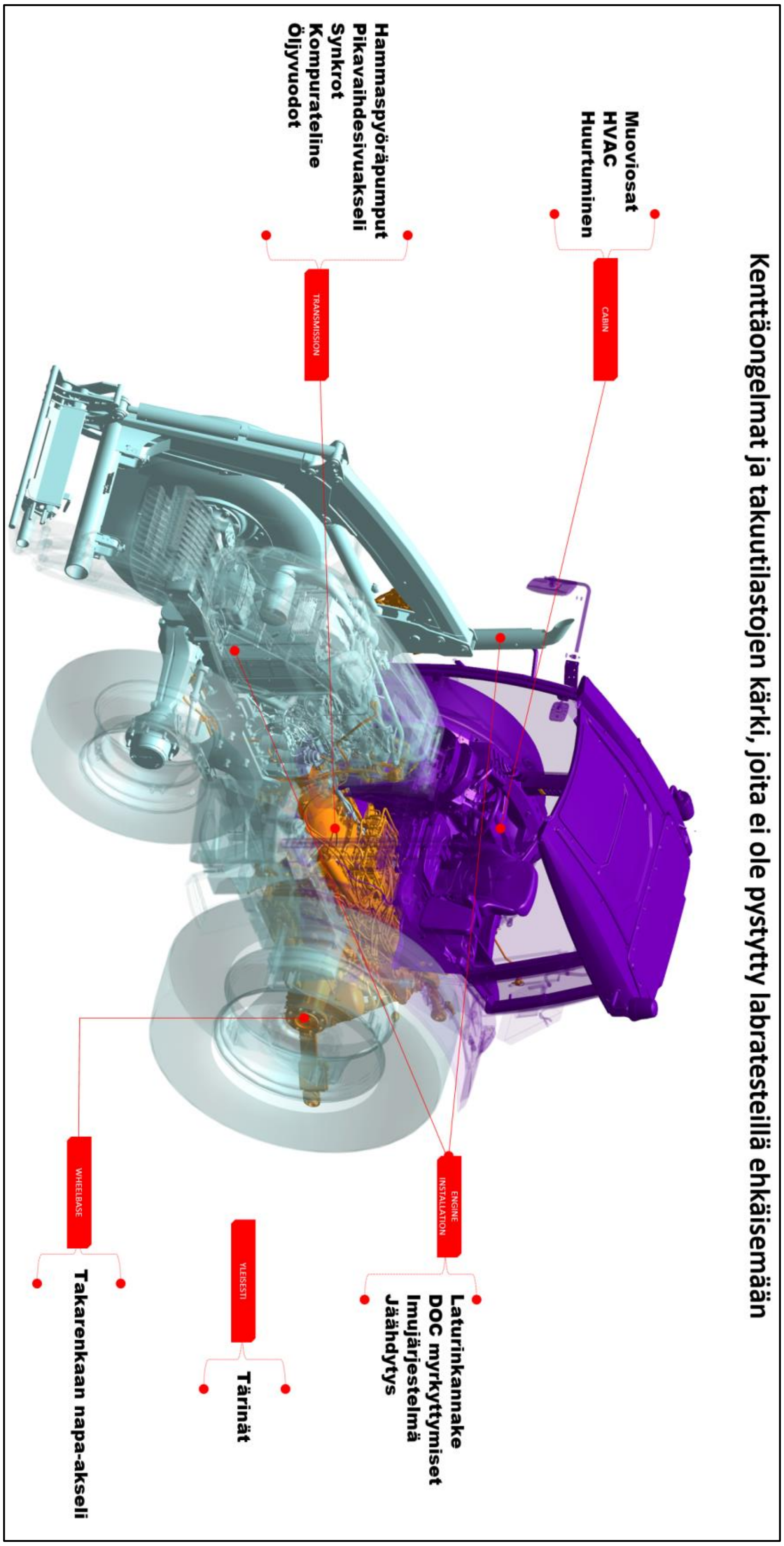
Most difficult laboratory tests



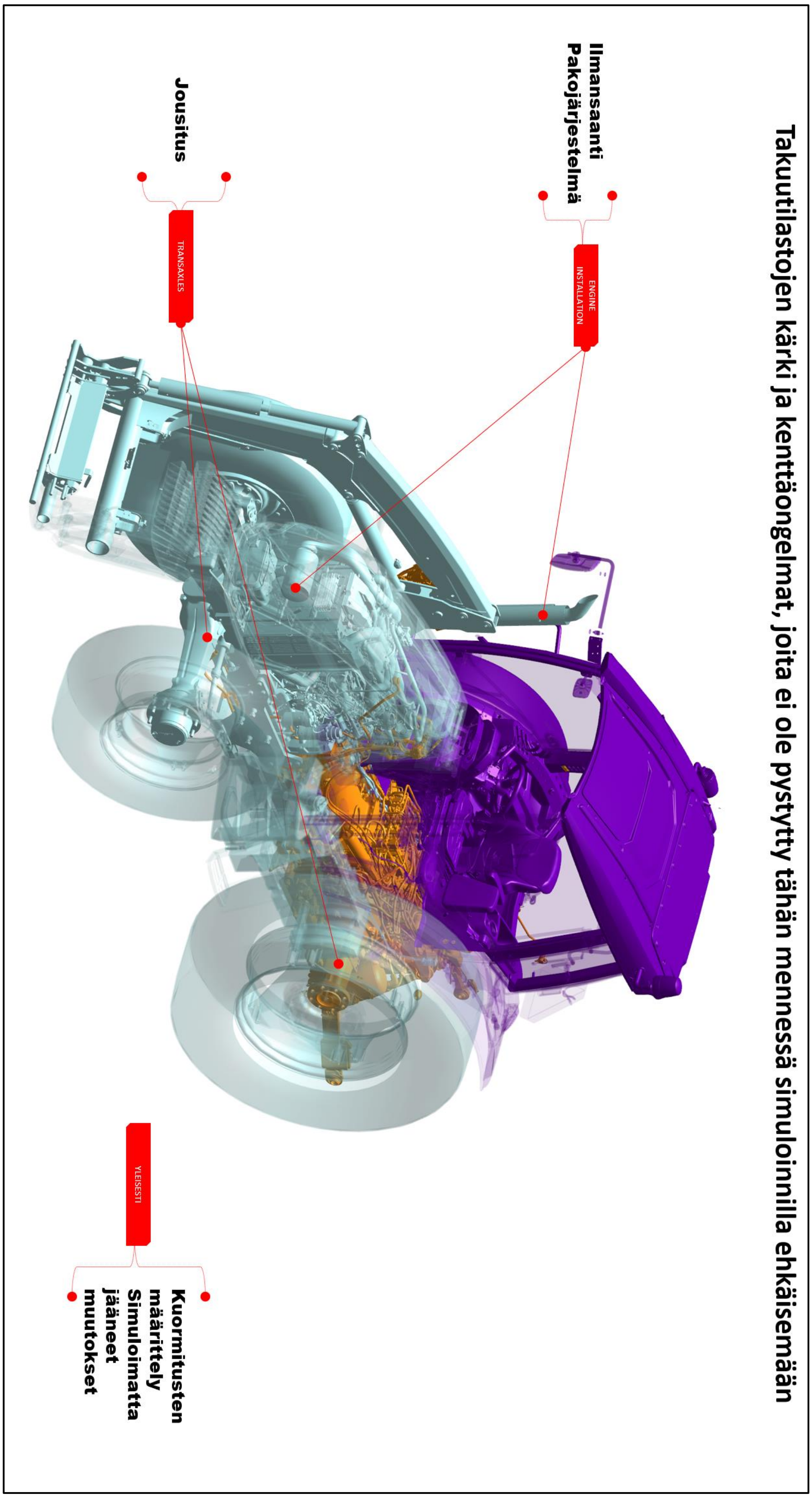
Most difficult simulations



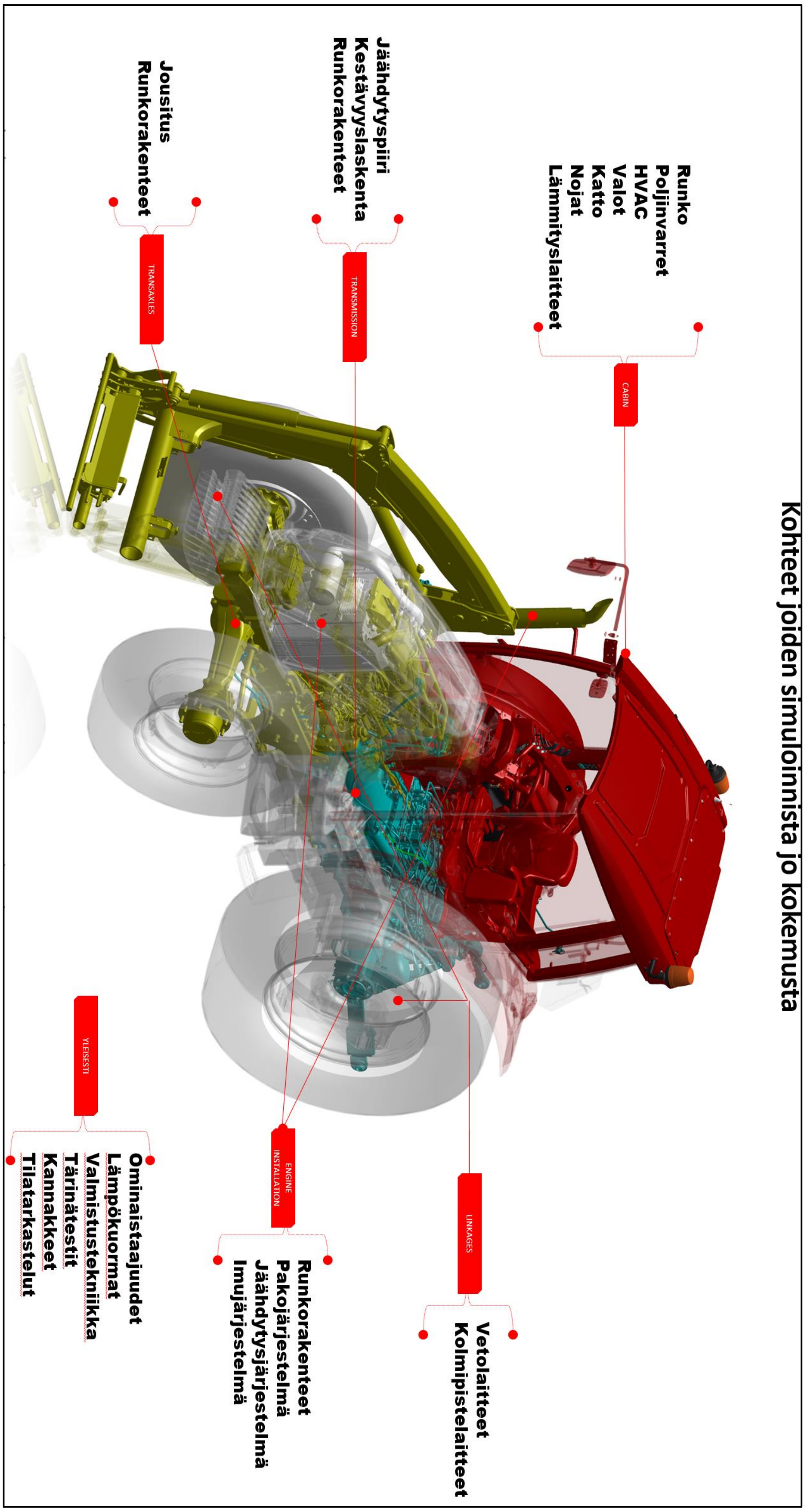
Field issues and warranty statistics, which could not be prevented through lab tests during the project



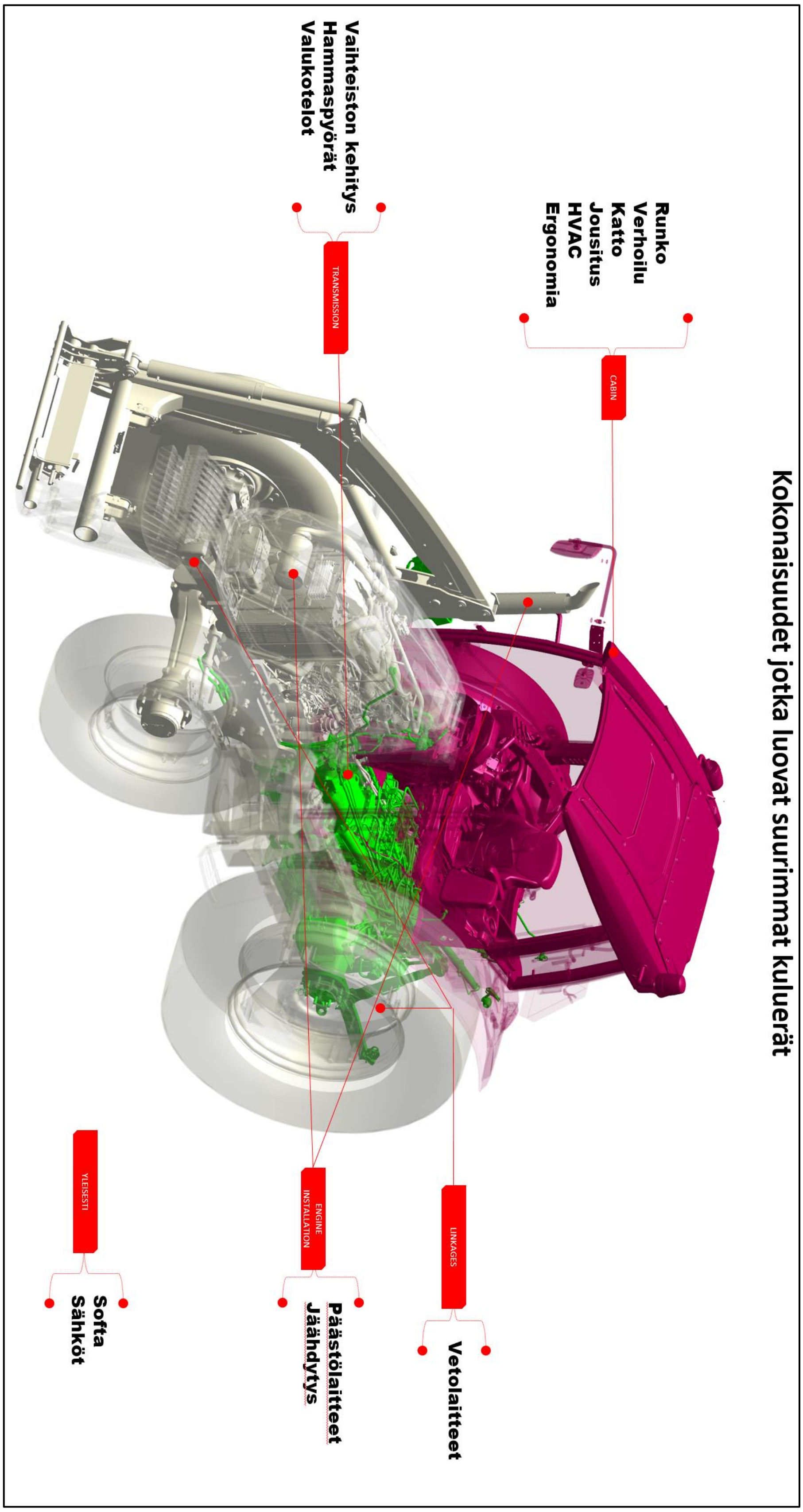
Field issues and warranty statistics, which could not be prevented through simulation during the project



Systems that engineers already have experience in simulation



Systems that create the largest expenses



APPENDIX XI

Module view of the possible simulation targets