TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

HENRI VAINIO

A DYNAMIC MODEL OF A LIFTING DEVICE AND ITS USE AS A TOOL FOR SMART SERVICES

Master of Science Thesis

Examiner: Professor Kari T. Koskinen
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Suomalainen metalli- ja koneteollisuus on muuttamassa liiketoimintamallejaan kohti palveluliiketoimintaa. Teollisuuden palvelumalleihin kuuluu elinkaaripalveluiden tarjoaminen tuoteen lisäksi tai äärimmilleen vietynä palvelun myyminen tuotteen sijaan. Valmistaja saattaa ottaa vastuulleen asiakkaan koko prosessin ja siihen liittyvät palvelut, kuten kunnonvalvonnan, huollon ja varaosat. Tällaiset uudet liiketoimintamallit vaativat uusia työvälineitä.

Simulaatio on ollut koneteollisuudelle tehokas ja monipuolinen työväline jo kauan. Tietotekniikan kehittyminen tekee simulaation käytöstä jatkuvasti tehokkaampaa ja käytännöllisempää. Käytössä on laaja kirjo simulaatiosovelluksia ja uusia kehitetään.

Tässä diplomityössä tutkitaan simulaation käyttömahdollisuuksia teollisuuden palveluliiketoiminnan työvälineenä, mikä tarkoittaa näiden kahden alueen yhdistämistä. Teollisuuden palveluille pyritään antamaan lisää älyä.

Diplomityö jakautuu kahteen osaan. Aluksi teoariaosuudessa tarkastellaan simulaation käyttöä nykypäivän teollisuudessa ja esitetään joitakin esimerkkejä. Tämän jälkeen rakennetaan simulaatiomalli case-yrityksen nostolaitteesta ja käytetään sitä esittelemään mahdollisia käyttötapoja simulaatiolle älypalveluiden työvälineenä.

Tutkimuksessa havaittiin, että simulaatiota on mahdollista käyttää useissa teollisuuden palveluiden sovelluksissa, jotka tukevat toisiaan. Yksi malli, joka on rakennettu toistamaan mahdollisimman monenlaisia ilmiöitä, esimerkiksi käyttäen mallinnustapana fysikaalista mallinnusta, voi toimia monen eri älypalvelun työvälineenä. Simulaatiomallien käyttöä on mahdollista tehostaa hahmottamalla ne osana tuotteen elinkaarta ja suunnittelemalla niiden rakentaminen ja käyttö tämän perusteella.

ABSTRACT

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Finnish metal and engineering industry is on the verge of a paradigm shift towards a service business approach, which means selling products bundled with related services. A more extreme approach of this is a manufacturer selling services and taking responsibility of the customer's entire process, including such things as condition monitoring, maintenance and spare parts. These new ways of thinking require new tools and new ways of using existing tools.

Simulation has been a powerful and versatile tool in the realm of mechanical engineering for a long time. The advances in computer technology are making it ever more effective and useful. There are many existing simulation applications and new ones are being developed all the time.

This thesis examines the uses for simulation as a tool for the industrial services. That means mating these two subjects, giving the industrial services more intellect through the use of simulation and thereby making them 'smart' services.

The thesis is divided into two parts. First, in the theory part current uses of simulation are examined and examples of present day simulation applications presented. Then a simulation model of a lifting device based on a case company's product is built and used to demonstrate possible uses for simulation as a tool for smart services.

The research shows that it is possible to use simulation as a tool in several service potential areas with the simulation applications supporting each other. A single model built to be a general representation of the object of modeling, for example by using the method of physical modeling, can be used in many different ways and as a tool for several services. The use of simulation models would be enhanced by seeing them as a part of a product's life cycle and by planning their building and use accordingly.

PREFACE

This Master's Thesis concludes a rather lengthy and eventful period of master's studies at the Tampere University of Technology. The thesis was begun at the department of Intelligent Hydraulics and Automation (IHA) and finished at the department of Mechanical Engineering and Industrial systems (MEI) as a part of the Future Industrial Services (FutIS) program. The departments and the program are gratefully acknowledged for funding this project.

I would like to thank my supervisors Kari T. Koskinen and Jussi Aaltonen for their guidance and ideas thorough the process of making this thesis.

Finally, I would like to express my gratitude and love for my family and my friends for being there for me, for supporting me and for making my life happier and very fascinating indeed!

Tampere, May 14, 2014

Henri Vainio

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

λ	Slip factor
λ_p	Peak value of wheel slip curve
μ	Adhesion coefficient
μ_p	Peak value of adhesion coefficient curve
ω_v	Angular velocity of vehicle
ω_w	Angular velocity of wheel
ω	Angular velocity
B_{rel}	Damping coefficient when solids are in stiction
e	Deformation needed for 95 % of contact viscous friction
f_{mt}	Force at a rope end
f_{mtca}	Force into the spring stiffness
f_{slip}	Dynamic (Coulomb) friction between solids
f_{stick}	Maximum stiction friction force between solids
gap	Gap between two bodies
k	Contact stiffness
K	Total stiffness
K_0	Stiffness of unit length of rope
l_0	Initial length
l	Total length
l_Δ	Lengthening

nr	Number of ropes
pen	Penetration
R	Total viscous friction
R_{vis0}	Viscous friction of unit length of rope
r_{visc}	Contact viscous friction
V_{rel}	Relative velocity between the two solids
v_{mt}	Velocity at a rope end
q_{mt}	Uncoiling at a rope end
AR	Augmented Reality
CAD	Computer Assisted Design
FIMECC	Finnish Metals and Engineering Competence Cluster
FutIS	Future Industrial Services
HIL	Hardware In the Loop
ICT	Information and Communications Technology
MSI	Maintenance Significant Item
PDM	Product Data Management
PLC	Programmable Logic Controller
PLM	Product Life Cycle Management
R&D	Research and Development
SIL	Software in the Loop
VML	Virtual Machine Laboratory

1. INTRODUCTION

Finnish metals and engineering companies are in a process of trying to integrate services into their business models. Traditionally such companies have designed and manufactured mechanical or metal products and sold them to customers. The current trend is to offer services in addition to the products, in order to extend the revenue generating business model to span the product's entire life cycle.

This master's thesis has been conducted as part of the Service business capabilities project of FutIS, funded by Tekes, companies and research institutes and coordinated by FIMECC, Finnish metals and engineering industry competence cluster. FIMECC has initiated a program for Future Industrial Services, FutIS for short, to investigate the possibility of shifting the industry from the product centric into service providers. The program is divided into three work packages, the first attempting to spread a service business mindset to the industry, the second looking into integrated service development and the third seeking to enhance service operations efficiency. (FIMECC FutIS 2013)

This endeavor opens up new possibilities for looking at mechanical engineering as a whole. Service operations spanning the entire product life cycle need structure, planning and new tools to be efficient. Many of these service business potential areas are already being fulfilled by some instance or other. Now, as the companies who design and manufacture the products seek to take over many, if not all, of the services related to their products as well as offering new types of service, they need to develop new modes of operation.

Product as a service is a new way of thinking, in which a product is offered as a bundle of the physical product and all of its assets as a service. The service provider owns the entire life cycle of the product and the customer pays for the services the product offers. For example a roofing company owns the roof and the owner of the house pays for the services provided by the roof, like protection from the weather. This makes it easier for the service providing company to control the entire life cycle of the product and all the related supply chains. This kind of focus on product life cycle lessens the fragmented ownership of physical goods and intangible assets that currently leads to unsustainable and wasteful actions, meaning an evolution from *cradle-to-grave* thinking into *cradle-to-cradle* thinking. (KITARA 2010)

This new thinking requires new tools to make it more efficient. Computer operated simulation and modeling is one of the tools already used by many existing service operations or industrial activities that can be seen as services. The new service business mindset makes these simulation models a tool for the industrial services, also called smart services as they are computer aided. This period of paradigm shift offers a good opportunity to look into simulation as a tool, examine what is already being done and what could be done in the future to enhance the service business as a whole.

Examining the uses of simulation as a tool for smart services requires discovering some definitions for industrial services and then finding out about the uses of simulation from their perspective. Based on the findings further development ideas for smart services can be suggested and examples made. This leads to the following objectives for the research:

- Find definitions for the industrial services
- Find examples of the use of simulation in these services
- Find out about and come up with future uses for simulation in smart services
- Build a model to demonstrate some of these uses

Firstly literary sources are examined in order to gain understanding on the state of industrial services and the simulation used in them. Then new possibilities for the use of simulation as a tool for smart services are discussed. After that a simulation model of a lifting device is built and used to test some of the potential service applications. The results from the simulation runs are discussed and joined into a larger perspective. Potential further development into service tools is suggested. Finally conclusions are made.

2. THE USE OF SIMULATION AS A TOOL FOR SERVICES

In order to examine the potential of simulation as a tool for industrial services both must be defined and a useful categorization for the models must be found. As the service business model seeks to make the manufacturer the owner of the product life cycle, a logical way to examine simulation models used by the industry is to follow a product's life cycle from the beginning to the end and find out how simulation is being used. This means a definition of a product life cycle model is also required. The use of simulation models brings with it other requirements and considerations, such as the handling of associated data and user issues. As this thesis is limited in scope, there are limitations to this review. The services and models discussed in the following will only be related to engineering industry and its processes. Examples from other domains may be mentioned where applicable, but will not be discussed in great detail.

2.1 Industrial services and their current state in Finland

A review of services and industrial services made by Paloheimo, Miettinen and Brax in 2004 lists five characteristics of services that separate them from tangible products. These characteristics are intangibility, inseparability of production and consumption, heterogeneity derived from standardization problems, perishability and ownership in the sense that in the case of services no ownership is transferred to the buyer. However, the evolution of communications and information technology clouds even these definitions, as digital services can be quite homogeneous and not necessarily perishable. (Paloheimo, Miettinen, Brax 2004)

One definition, by Lalonde and Zinszer, classifies services into three categories: pre-sale, sale-related and post-sale services (Lalonde, Zinszer 1976, cited in Ahvenniemi 2012). Pre-sale services include activities that help the customer make the decision to buy. Sale-related services are services that take place during the sale and the beginning of use of the product, such as installation and training. Post-sale services include maintenance related activities and are the ones most often perceived as services. (Ahvenniemi 2012) This classification supports the idea of examining services in a linear order, following the product's life cycle.

Presently pervasive networking and life cycle management philosophies are turning products into *platforms for service delivery* (Huovinen 2010). The trend is to bundle services with products and gain easier control and more profit for the manufacturer. Services can be seen to follow the product from its initial conception to its recycling and replacement. The concepts of product and the associated services are beginning to fuse together. The use of simulation as a tool to support this service mindset can also be seen to begin with the very first concept models. This gives a first hint of a larger picture of how best to employ models as tools.

Finnish engineering industry offers several services for its customers and is currently attempting to expand this service business potential. The following companies are all part of the FIMECC FutIS program and have invested in their service business applications. A quick internet survey reveals a list of services these companies claim to offer.

KONE manufactures elevators and escalators. Their Service-branch offers project planning services and tools for designing buildings, for example design software to aid elevator selection. They also offer project management and installation services and construction solutions for use during the building phase. During the operation of their products they provide maintenance and monitoring services, recording and tracking of operation information, service records and technical data. They offer spare parts, modernization service of old equipment and analysis service of the equipment. (KONE 2014)

Konecranes manufactures cranes and cargo lifters. They offer training for users and maintenance personnel, data collection and analysis, tech support, maintenance, modernizations, spare parts, inspections and reliability surveys. (Konecranes 2014)

Cargotec and its subsidiaries Hiab, MacGregor and Kalmar manufacture cranes and other lifting devices. Their service offering includes spare parts and logistics, inspections and certifications, repair and maintenance, crane services, total operations maintenance, training, rental and pre-owned equipment, technical support and installation services. (Hiab 2014) (Kalmar 2014) (MacGregor 2014)

Metso Mining and Construction manufactures mining equipment. They offer spare parts, supervision and maintenance, training, repairs and refurbishments, Engineered-To-Order upgrades and retrofits, as well as performance contracts with varying levels of service included, in order to take care of the performance of their products in use. (Metso Mining and Construction 2014)

Outotec provides technologies for metal and mineral processing industries. They offer technical services from ramp up of new production to the decommissioning of a plant, maintenance planning, modernization either to refurbish or upgrade a production line, process optimization, operations and maintenance responsibility, inventory management, maintenance shutdown planning, performance reporting, remote control and monitoring services, spare parts and inspection services. (Outotec 2014)

Almost all of the companies offer, in one form or another, the following services: training of users and maintenance personnel, data collection and analysis, technical support, condition monitoring, fault detection, repair and spare parts and installation of product. Table 2.1. summarizes the services offered by the companies.

Table 2.1. The services offered by the FutIS participant engineering companies.

	KONE	Konecranes	Cargotec	Metso	Outotec
R&D	x	x			
Production planning	x				x
Training		x	x		
Installation	x	x	x	x	
Condition monitoring	x	x	x	x	x
Maintenance	x	x	x	x	x
Tech support	x	x	x	x	x
Retirement					x

As can be seen in the table 2.1., all of these companies have already invested in developing their services. The FutIS program also includes steel manufacturing companies, such as Rautaruukki. Their products have less service potential areas, but they attempt to compensate for this by investing in research and development applications, where the customer is able to develop ideas together with the R&D departments of the steel company. (Ruukki 2014)

The participation of these companies in the FIMECC projects further implies that they represent the service oriented mindset and therefore represent the kind of future examined in this thesis. Other companies may still hold a more product-centric view.

2.2 Definitions of product life cycle

Since the product is seen as a service delivery platform and services can be categorized based on the events in the products life, it is logical to examine the use of simulation following the product life cycle model. Product life cycle means the existence of the product from initial conception to retirement. This life cycle therefore includes everything happening to the product, from design to recycling and includes all the service potential areas related to the product.

There are three phases in the product life cycle according to John Stark (2011). The Beginning-of-Life includes imagination, definition and realization of the product. The Middle-of-Life phase includes product use, support and maintenance. Finally there is the End-of-Life phase, including activities such as product retirement, disposal and recycling. (Stark 2011)

Eight primary life cycle functions can also be recognized, they are development, verification, manufacturing, deployment, training, operation support and disposal (Systems Engineering Fundamentals 2001). With only a little variation they seem to correspond to the services offered by the FutIS participant companies.

The realization of the service potential in these life cycle phases can benefit from the utilization of simulation. It is again a matter of definition if the simulation applications already in use are seen as tools for services, but labeling them so might encourage manufacturers to invest in simulation and would also help to form a larger picture of the many uses of simulation for the purposes of smart services.

2.3 Definitions and types of simulation

A simulation model, for the purposes of this thesis, is defined as a mathematical representation of a real system. Simulation can be defined as “Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system” (Robinson 2004).

Several types of simulation models exist and simulation can be executed in various ways. Models can be used to simulate dynamic behavior, events over time, or a static situation, a point in time. Dynamic models can be classified as continuous-time or discrete-time models. The former calculate the values of their variables continuously over time while the latter change these values only at certain points in time. Sometimes models are used to describe phenomenon using probabilities of events within the phenomenon to determine the next state of the system. These are called stochastic models. A deterministic model on the other hand assumes causality between events, in other words a cause and effect scenario where there always exists the same cause for effect. All of these types of models are quantitative, meaning that their variables are represented numerically in a quantitatively measurable scale. It is also possible to create less accurate models, called qualitative models, where the variables are not related in a linearly measurable manner and which are always discrete time models. (Fritzson 2011)

2.4 Models used during the product life cycle

A product begins its life in the minds of designers. Simulation, defined in the broadest possible way, has been a tool for planning new things for hundreds, if not thousands of years. With the coming of computer technology, mathematical models have shifted from paper to a digital form and provided tools for engineers to prototype and verify their solutions before anything physical is built.

The concept of a simulation model has originated as a tool for product development. As the computer technology advanced, simulation became more and more commonplace and specific simulation software were developed. Simulation is commonplace in today’s engineering industry and can be found in many of the service potential areas of a product’s life cycle.

2.4.1 Uses of simulation in Beginning-of-Life phase

The beginning of life of a product includes, according to Stark (2011), its imagining, definition and realization. That includes product development, production planning, marketing, installation and training, all of which are service potential areas for engineering industry.

Product development has traditionally used simulation to great extent. The production planning of the factory where the product will be installed would normally be handled by the customer, but simulation can be used to aid the said production planning as a service, especially if the manufacturer assumes ownership of the entire product life cycle. Marketing can use simulation as an argumentation tool. When the product has been sold, several potential services become available. Installing the product and defining its parameters is a potential service, as is the training of the end users. Some of these services have always been included in the sale, while some, such as basic safety training, are sometimes required by law. Others can be sold as extra, or included in the original deal to make the first decision of purchase more compelling. Simulation models are used to aid these services to some extent, but presently there is a great potential for enhancing these services with simulation.

The product development phase of the product's life cycle includes multiple widely used simulation applications. While it is a matter of academic debate whether or not product development itself is an industrial service or just a part of the manufacturing process, it is clear that the abundance of simulation software and their frequent use mean that it is worth examining. Companies are already using this software, which means it would be easy to adapt it for different uses as tools for services.

Digital prototyping allows the creation, validation, optimization and management of designs. This way the entire design process, from conceptual design to manufacturing phase, is more efficient and innovative. Digital prototyping makes it possible to visualize and simulate the real world performance and characteristics of the design. This reduces the need to build physical prototypes, saving time and money. (Argusa, Mazza, Penso 2009) Design and prototyping can also include the development of control systems and specific components or subsystems of the product, such as hydraulics or electrics. Verifying the possibility and availability of the assembly of the product can also be done using simulation (Sato, Hashima, Senta 2007).

Developing the product further can include hardware-in-the-loop simulations, which means testing a physical component as a part of the simulation, for example controlling an actuator with values gained from a simulation model of its control system and operating environment. Software-in-the-loop simulation on the other hand means running software designed to interact with physical systems in simulated environment, where these physical systems are replaced by a model. (Sato, Hashima, Senta 2007)

One of the latest innovations in computer-aided engineering is a virtual machine laboratory. A virtual machine laboratory is defined as "any environment that can be used to demonstrate a function and structure of a working machine" (Salonen et al. 2011). The Semogen project of the Smart simulators research group at TUT researched the automatic generation of a virtual machine laboratory (Nurmi 2013). The project defined their VML as a software environment meant for the visualization of simulation, diagnostics, documentation, functions and structure of a machine system. A VML can be used for teaching the working and operation of a machine, for co-operative designing, for development and virtual prototyping. A model based real time simulation is used to examine the interactions and behaviors in the machine system. (Nykänen et al. 2013)

There are other VML-like applications already in the market. Dassault Systèmes for example offers a product life cycle management system, which allows for the examination of the entire product life cycle of a machine in a virtual environment. 3D visualizations are offered for design, production, marketing, maintenance and recycling applications. (Nykänen et al. 2013)

Production planning is a pre-sale-modeling application more traditionally adapted as a service. Models of entire factories or production chains offer a chance to test solutions on a very large scale. Modern simulation technologies allow for optimizing the production chain. (Law, McComas 2000) It is also possible to simulate warehouses and develop control systems for them (Lakka 2013).

Assembly line operational procedures and working methods can be verified and validated. Especially robotics work cells have for years been configured using simulation. (García Pájaro 2012)

Production planning happens for existing factories too. Changes in the products manufactured, in the manufacturing process, new machines, optimization of production, there are many reasons to change the existing production system and these changes need testing, verification and validation. Simulation allows this to be done without costly pauses in production and offers a way to find out optimal solutions and verify them before any changes are made in the actual factory.

Marketing uses simulation models of the products as an argumentation tool. These types of simulators allow the potential customer to experiment with the product or are used to demonstrate the effectiveness of the product in the case of the said customer. There already are such simulators in use, such as the ABB RobotStudio Plastics Sales tool shown in figure 2.1.

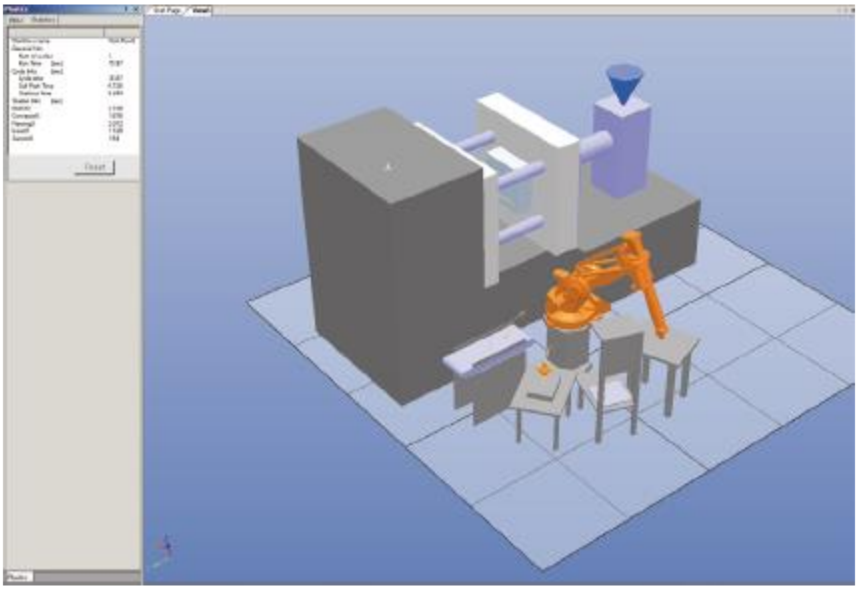


Figure 2.1. *ABB RobotStudio Plastic Sales Tool visualization view* ***(****RobotStudio Plastics Sales Tool 2006).*

The sales tool offers the possibility create a simulation of the customer's work station and to show the operation of the robot being sold as a part of the customer's process as shown in figure 2.1. This can be used to augment the sales argument and to allow the customer to examine the uses of the robots. (RobotStudio Plastics Sales Tool 2006)

The training of the users of a product is a potential service to be sold. Simulators have been used for training purposes for quite some time, as they enable the training to take place anywhere. Using a simulator also leaves the actual product or production line undisturbed (García Pájaro 2012).

One example of a training simulator is the John Deere forestry machine simulator. A harvester simulator interface is shown in figure 2.2.

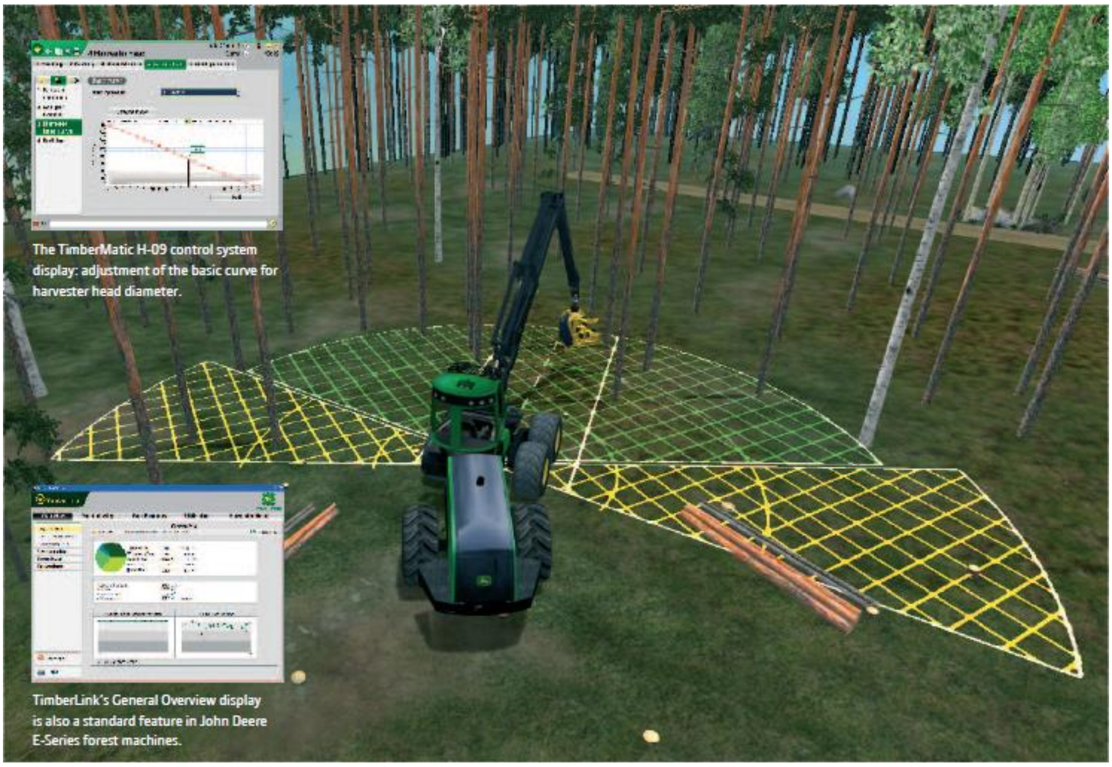


Figure 2.2. *John Deere forestry machine simulator interface (John Deere 2010).*

The simulator enables the user to operate a forestry machine with real control equipment in a simulated forest environment, offering the possibility to train every important aspect of the actual operation of these machines, including co-operation with several simulators linked together. It does not, however, simulate fault situations. (John Deere 2010)

Another important group of people requiring training is the maintenance personnel. Research has been made in the field of virtual machine laboratories that allow the inner workings of a machine to be examined during its simulated operation. It is also possible to simulate fault situations. (Nykänen et al. 2013)

An example of maintenance personnel training application is the Metviro training simulator for forestry machine maintenance mechanics, some functionalities of which are shown in figure 2.3.

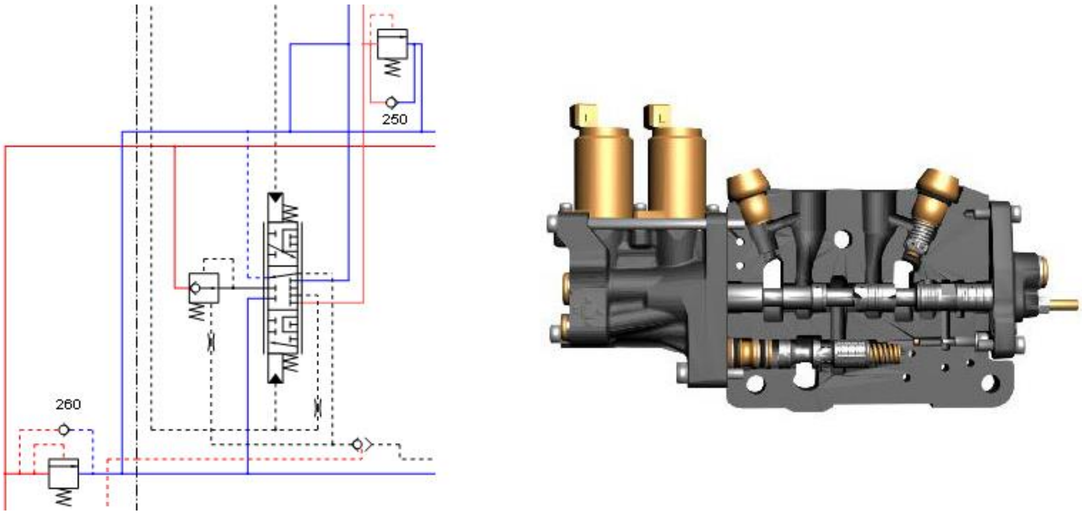


Figure 2.3. *Metviro dynamic hydraulic schematic and a 3D visualization of a valve block (Metviro 2009).*

Metviro offers visualizations of the machine operation in diagrams and 3D images of the machine, as seen in figure 2.3. Included are also simulated fault modes, AI fault diagnosis, operating models of experienced mechanics and tools to support teaching and learning. (Metviro 2009)

Installing a product often includes calibration and control system parameterization. Simulation results give a starting point for the calibration process. Off-line programming of PLCs, programmable logic controllers, and robots allows the programming to be done before the installation of the product, or in case of an existing production line, testing the new parameters by simulation without interrupting the production (Rodriguez Alvarado 2010).

The calibration of the product depends on its operating environment and there can be considerable differences between the parameters of the same type of product. This is apparent in process industry, where the operating environment often affects the definition of normal operation. Tools for automatically setting the nominal values for actuators during the process of commissioning are lacking and this parameterization is often done using default values, which do not take into account the variations in the environment. (Huovinen 2010)

2.4.2 Uses of simulation in Middle-of-Life phase

Stark (2011) identifies the middle-of-life phase of the product to include use, support and maintenance related activities. After the product has been sold, delivered and installed and is in use the applications traditionally seen as services become available. This is where most companies see their service potential and these services are the most researched (Ahvenniemi 2012). It seems to follow that the models used in these services are also easiest to see tools for service business.

Condition monitoring and fault detection are a major area of interest for the industrial services. These days a maintenance shutdown means maintaining all the machines, even the ones that do not require it yet, since halting a production line costs so much.

The ISO 13372 standard defines condition monitoring as the detection and collection of information and data that indicate the state of a machine. The same standard defines prognostics as an analysis of the symptoms of faults to predict future condition and remaining useful life. (ISO 13372 2004) The main objective of prognostics is to determine the need of maintenance at a given time (Lumme 2012).

Monitoring and diagnostics algorithms in use can be assigned in one of three categories, which are quantitative model based methods, qualitative model based methods, and process history based methods. The model based methods use a simulation model built based on the physics of the process. Quantitative models are built using mathematical functional describing the relationships between the inputs and the outputs of the system modeled. Qualitative models describe these relationships using qualitative functions. History based methods analyze historical process data. Some methods of condition monitoring are better suited in some situations than others and using several methods in conjunction would probably be a good idea. (Huovinen 2010)

It is possible to create a classifier algorithm that is able to distinguish abnormalities in machine condition data, learn from past data and, given a large base of installed machines producing condition monitoring data, learn from one machine and apply the knowledge to another. This is called intelligent interpretation of machine condition data. A continuously learning classifier detects faults and predicts failures and operational time remaining. (Lumme 2012)

Technologies to enhance on-site maintenance work are also being developed. Augmented Reality technology consisting of a pair of AR-goggles and video streaming over the internet to connect with a central hub offers the maintenance personnel expert advice from the maintenance headquarters or from the system supplier. The aim is to reduce the costs caused by unplanned maintenance by making it more efficient to perform accurate fault diagnosis and to plan and execute the maintenance. The technology also aims to increase knowledge and improve the processes included in the product life cycle, to provide feedback on maintenance activities along the life cycle. (Smith et al. 2011)

2.4.3 Uses of simulation in the End-of-Life phase

According to Stark, the end-of-life phase of the product life cycle includes the product’s retirement, disposal and recycling. As environmental values continue to increase their meaning, recycling especially becomes important. Also, the retirement procedures of a machine take planning. There are many possible service potential areas in the end-of-life phase, though not all of them seem to be fully realized.

Legislation and the need to preserve natural resources require new attitudes and technologies to the reuse of components and recycling of products. The dismantling of electrical scrap and its enhancement by a systematic planning of this process has been studied. Planning the disassembly of such devices is even more complex than planning their assembly. Disassembly lines must be able to handle many types of products, although processing only one type of product would save time and resources. To examine this problem, a computer assisted analysis modules implemented into a software tool called LaySiD has been created. Its operation consists of four steps. It identifies the characteristics of the devices to be scrapped and the boundary conditions of the disassembly surroundings, using a model of the product and a model of the dismantling process. The products are then classified into disassembly families. Then layout alternatives for the disassembly system are generated and the efficiency of these alternatives is tested using simulation. Finally algorithms calculate the characteristics of the system layouts and comparing these gives the optimal layout of the disassembly system. This tool allows the organization and optimizing of disassembly processes. (Hesselbach, Westernhagen 1999)

2.5 Data-architecture requirements

Simulation models need parameters defining the physical system they emulate and the control values to drive the simulation, as well as possible environmental parameters defining the working environment of the product. Simulation also produces very large amounts of data of varying levels of accuracy and usefulness. It is not enough to have a good model. To utilize simulation efficiently as tool a large number of applications requires some sort of a data-architecture to facilitate the models' needs for data and to process and store the data produced by simulation. This data needs to be available regardless of physical locations. For example a predictive maintenance planning simulation could be offered as a service by the manufacturer of the product and the simulation might be run far away from the actual product's location.

The parameters of the machine are initially available from the design data and from measurements made during installation. As a machine operates, these parameters will gradually change as wear and replacement parts change its physical behavior, requiring updates on the parameters of the model. Some applications require measurement data from a particular instance, such as a fault situation. These are available from recorded sensor and command data, though in some cases the sensor data might even come from another simulation model.

The data produced by the models is raw and numerical. Simulation software, as a part of their function, offer visualization possibilities for this data, such as numerical displays or graphs, sometimes even images and 3D-representations of the machine being simulated. The accuracy and usefulness of this data depends on the accuracy of the model and the parameters used for simulation. The storage, analysis, refinement, availability and distribution of the simulation data is important also because of the exponentially increasing amount of data created by modern industrial systems. This industrial data takes the forms of historical data from recorded measurements and simulations, real time data from sensors and future data, predictions made based on simulations (De Vin et al. 2005).

A data-architecture should allow different simulation applications to publish and request data, interconnect with other applications regardless of geographical location and allow new applications to integrate with it (Rodriguez Alvarado, J. 2010). One approach to the data handling is called Information fusion, defined as “the study of efficient methods for automatically or semi-automatically transforming information from different sources and different points in time into a representation that provides effective support for human or automated decision making.” (Boström et al. 2007)

The proposed Information fusion model suggests fusing data gained from the process through sensor, data from historical databases and data from simulation models to give a comprehensive view of the process to aid in decision making. It also requires a so-called active database, which means a database that analyzes the data stored and identifies trends and events in it. The information fusion process is demonstrated in the figure 2.4.

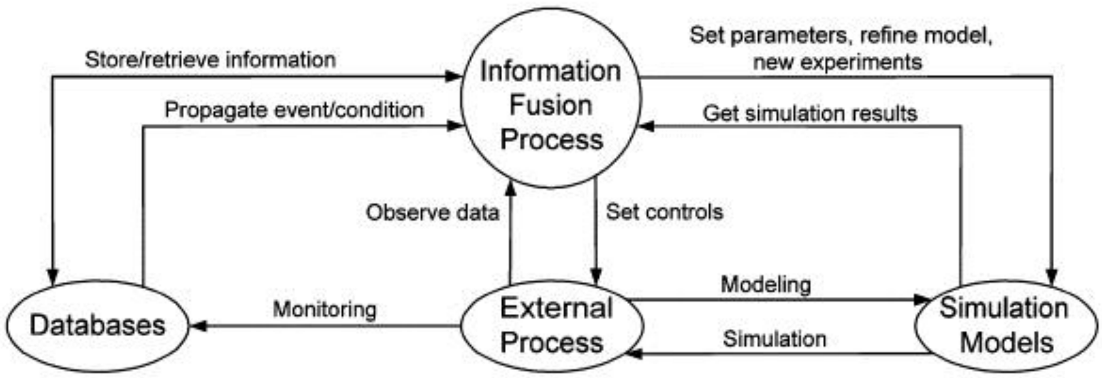


Figure 2.4. *The extended information fusion model for service and maintenance support (De Vin et al. 2005).*

Figure 2.4. shows the information fusion model with its internal interactions. Historical data in the databases, sensor data from the process and future predictions from simulation models are all fused to give information about the condition of the product.

A functioning PLM system makes the product life cycle more transparent and thereby enables faster to market times, better support for the users and better management of end-of-life (Huovinen 2010). Current PLM systems and tools are most heavily focused on the beginning of the life cycle, because it is the phase easiest to manage and control. All the data, information and knowledge creation during the beginning-of-life phase happens inside the company. Attention is shifting towards the middle-of-life. (Vainio 2012) This further implies the need for development of unified data-architectures capable of interacting with sources outside the company, such as receiving condition monitoring data. Simulating the entire product life cycle in order to help plan and manage it is also possible (Fukushige, Yamamoto, Umeda 2012).

2.6 Taking users into account

It is important to keep in mind the users of the simulation models and make them intuitive to use and easy to understand. Users often have limited knowledge on how to use the simulation software or are not aware of all of its functions.

The use of simulation models and applications should be easy and require only basic computer skills. Usability is often neglected in academic work, but the end users of many of these models come from different branches of organizations and have very different education and experience backgrounds. (Huovinen 2010)

Users may not understand the importance of recording all the data they produce in their work and may be against new tools and changes in the design process. Designers often focus on a single problem instead of seeing a bigger picture of the design process. They may be unaware of how the design data will be used in the future and how it should be documented. The storage of all data is not always seen as necessary and can even be regarded as a useless activity. As a new methodology is adopted, it needs to be introduced to an organization and spread with concrete, action oriented training. Even basic knowledge on such issues as PDM may be lacking, so basics cannot be ignored. The tools must be extremely simple to use, so that the user can concentrate on the actual work, bearing in mind that both the designers and the mechanics are user groups for the software. The biggest problem in the design process is the transfer of information from one person to another. Designers want views that combine different engineering disciples. (Nykänen et al. 2013)

Legal issues should also be remembered. Data accessibility brings risks, as remote connections to production sites are a source of security issues (Huovinen 2010). As well as security, data ownership and data privacy are issues which must be carefully considered (Paajanen, Kuosmanen 2010).

2.7 Visualizations used to enhance simulation

The visualization of the data and information gained from the simulation, keeping the actual users and their skill levels in mind, is quite important. A 3D visualization of the simulated product can offer significant advantages and increased efficiency by making the information easy and intuitive to understand (Argusa, Mazza, Penso 2009). An example of intuitively understandable information is shown in figure 2.5.

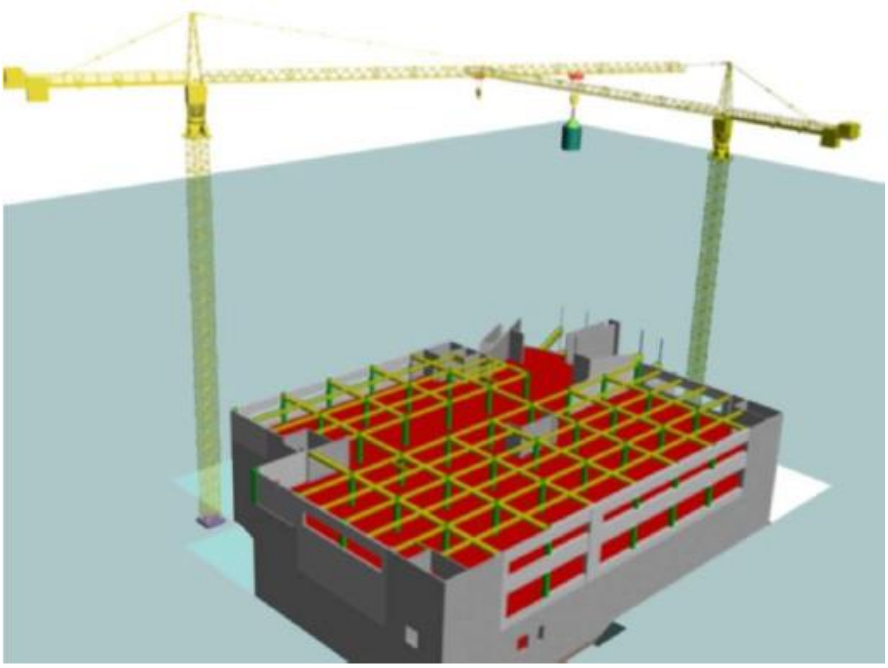


Figure 2.5. *Crane lifting route collision examination using a 3D visualization (Al-Hussein et al. 2006)****.***

Figure 2.5. shows a visualization of two tower cranes moving at a building site. Visualizations offer the decision makers a way to better understand simulation results. Dynamic graphical depictions, in other words real time 3D visualizations, which show what the operation of a device would look like in reality, give the decision makers a better understanding of the simulation results and operations of the device being simulated. Visualizations also display spatial limitations of the operation of the machines clearly, as can be seen in figure 2.4. (Al-Hussein et al. 2006)

A 3D image is an effective and natural way to allow the user to understand large amounts of data and have an understanding on the entire system. 3D software tools and plug-ins and pre-built 3D data are offered by several companies. Globally 3D technology is used by artists, programmers and even hobbyists in games, videos, movies and graphic arts. (Argusa, Mazza, Penso 2009) 3D CAD models originally created for product design purposes can be used to build a 3D visualization of a production line, which can then be used as an intuitive tool of monitoring the entire system (García Pájaro 2012). Especially important are co-operative views between different engineering disciples and the successful visualization of the design material (Nykänen et al. 2013).

2.8 Challenges faced by the use of simulation

The use of simulation in the ways described brings with it challenges. Data aquired from measurements or other simulations may be lacking. There might be erroneous data, missing data, or simply false data (Lumme 2012). Sometimes the design data created and used during the design process is badly recorded and difficult to find afterwards; examples of this include sketches made on paper pads, calculations made with math software and the tacit knowledge that slowly accumulates among the designers (Nykänen et al. 2013). Another example of this is factory plans and conveyor sequences being planned, developed and drawn with tools, for example office programs that do not create results reusable with PLC programming (Argusa, Mazza, Penso 2009).

The storing of the design data faces the problem of compatibility, because the software companies have no interest in providing common application programming interfaces or storage formats. Agreeing on the modeling methods of information is another challenging problem (Nurmi, 2013).

Modes of operation and data formats are not always compatible. It may be physically impossible to store all the data created. The storage of design data suffers from the differences in the data types, from 3D-CAD models and blueprints to the codes of the control systems and electrical diagrams. The management of design data uses different kinds of PDM and PLM programs but these vary greatly and also use different storage formats and methods. These formats and methods for a similar type of data may even vary inside a company. A lack of standards and compatibility between different types of software means that data transfer between models has to be done by hand. Different engineering domains, such as hydraulics, electrical engineering and mechanics often have their own models which do not interact (Nykänen et al. 2013).

One problem is the physical distribution of the models. A global company may not have the models available for all of its departments and even if it does, interaction between the models becomes a problem. Often the same product is modeled many times with different software that do not interact. For example, an R&D department creates a mathematical model of the machine with mathematical software while at the same time a marketing department models the same product using a video game physics model. (Rodriguez Alvarado 2010)

Problems arise when new design solutions have been reached by modifying old solutions. The physical product therefore acts as a sort of a collective memory of the design steps, from which data is difficult to extract from and use in VML applications. A large amount of information is missing and cannot be produced by any tool. (Nykänen et al. 2013)

The vastly varying operating environments of some products, such as mobile machines operating outdoors, place limits or at least challenges to some utilizations of simulation. Measurement data becomes more difficult to obtain and interpret.

Limits of simulation must also be understood. A model is usually accurate only inside certain limits of operation and includes simplifications which affect the way the results must be interpreted. Assuming that the results from the model can be applied to all cases in real life or trying to force reality into the constraints of the model can lead to problems. (Fritzson 2011)

Future developments in ICT will also have an impact on the utilization of simulation as a tool. The simulation software as well as the data handling programs will be updated, possibly causing continuous compatibility problems. The system must be able to adapt to radical new evolutions in information technology, such as cloud computing, cyber-physical systems and the internet of things.

3. POSSIBLE USES FOR SIMULATION IN SMART SERVICES

Considering the potential of utilizing simulation as a tool on one hand and on the requirements of successful use of simulation on the other, it is clear that the most efficient way of utilizing simulation is not to view the applications as separate instances, as individual tools for individual purposes. Creating the models and the data architectures needed by them would mean doing the same work over and over again, costing time and resources. A more systems engineering based approach to simulation would be more effective. Simulation is used to enrich data into information. All of the service potential areas in the product life cycle create data. This data can be turned into information to support the services.

As mentioned above, the entire product life cycle can be simulated and should be seen as a single entity, contained in a PDM system. It is this digital entity which provides the manufacturer many tools for physical services, but also digital ones. Data refinement into information is a service. Who owns and control this entity, the manufacturer or the end user, is an issue to be considered.

3.1 Enhancing product development through data-architectures

All of the simulation applications, any industrial internet applications and the industrial service business create large amounts of data related to an engineering industry product. If legal issues permit, all of this data could be available to the manufacturer’s R&D department, giving it the ability to analyze the entire fleet of products and its development needs. For example condition monitoring and fault detection data would, in a large scale, give a good idea of the problems in the product and could be used to direct the research and development. Information on the maintenance operations and spare parts used during a product’s life cycle could be used as a basis for designing products that work optimally for the duration of their life cycle instead of being optimal when they are new. Information of the product’s intended work cycle could also be used to simulate the strains and stresses occurring during normal operation, which could in turn be used as a source for optimizing the design. If the product is modular and its intended work cycle is even roughly known, the configuration of a particular product could be created automatically, using simulation to compare the efficiency of possible configurations through the entire operational phase of the product’s life cycle. This would of course not take into account spare parts and such, but give information of the configuration that would best meet the optimization criteria over the entire life cycle.

Command logs would give an idea of how the product is used, if all of its features are being utilized and thereby direct the training of users and promotion of features in marketing. Data from training simulators and marketing simulators could also be fed back into the product development phase, to direct the production planning based on early user demands and questions raised by the future users testing the simulators. The end of life simulation results could also be used in for example planning the structure and the materials of the product in a way to facilitate easier recycling operations. Information on all spare parts applied by the end of life of a product would indicate which parts of the product are being replaced during its life cycle. Further analysis could lead to either product development or maintenance routine updates. Also interaction between product planning and production planning is needed to ensure that the assembly of the product is efficient in the production facility (Brunsmann, Wilkes, Brocks 2011).

Research and development simulation can be offered as service. The company can create a simulation environment of its own and offer clients analysis services performed on back-end cluster computers, eliminating the need for the clients to create their own analysis environments (Sato, Hashima, Senta 2007). The manufacturer of a product, having created models of the product during the design process, can work with a client’s R&D department, offering simulation results to verify the client’s plans and designs, like for example some steel manufacturers already do. Automatic generation of simulation models based on parameter data has also been researched (Nykänen et al. 2013).

The manufacturer could also offer its simulation models to the client, either as a part of the sale of the actual product, or as an extra item for sale. This would become a profitable business if the models would be able to interact with models from other manufacturers, allowing the client to amend their own simulation environment, for example a model of their factory.

3.2 Planning and optimization of production

The ability to simulate and optimize an entire production line saves resources, as there is less need to test it, either while building a new production unit or halting an existing one for upgrades. Factory level process models can be used to optimize industrial processes. If measurement data is added to this, the industrial process could be adjusted in real time based on the analysis of the data. The simulation could be used in comparing different solutions to the problems detected with the measurements, arising both from the behavior of the machines and the behavior of their users. The solutions could also be tested with the existing physics model of an individual machine to simulate the condition monitoring issues caused by the modifications to the process.

The use of a machine installed in a factory is planned in this life cycle phase and the production planning may need to test how the machine acts in certain scenarios. A universally compatible model from the manufacturer of the machine would be a useful as a tool at this stage.

The changes in the existing production process mean changes in the work cycles and mechanical strains experienced by individual machines. This in turn has implications on the maintenance schedules and expected lifetimes of the machines. Taken to the component level, models of individual machines can be used to evaluate the impact of changes in the larger process, offering more detailed data for the purposes of verifying these changes and planning the use and maintenance of the individual machines with better accuracy. This type of service can again be offered to the client by the manufacturer.

If the manufacturer of the machine takes over the operations and maintenance responsibilities of the entire process, then these tools become a part of the manufacturer's service operation. The process can be adjusted in real time based on optimizing the factory output, the maintenance needs and other criteria.

3.3 Models as marketing tools

A model of a product with added visualizations can be used as an argumentation tool for marketing. A model depicting the physical behavior of the product and its control systems gives a potential customer the chance to test the product and its properties and features during the sales situation. Such a simulator will give an accurate and detailed idea of the workings of the product in question. Since the simulation does not need to be extremely accurate from the point of physics to convey the needed information, simplifications can be made in the model, making it faster and requiring less computational power. The model can then be run, for example, on a sales person's laptop computer. An argumentation tool like this requires a presentable visualization of the product. The visualization could be created using a video game graphics engine.

A physics simulator of the product can be amended with calculations to support the sales arguments. The model can be used to calculate mechanical stress, actuator behavior and estimated product service life. Several simulation runs with different parameters, such as an existing machine used by the customer, the new product being offered and any special features of the new product in action, will then produce comparable data sets that can be used to demonstrate the gains the new product would offer to the customer. Even though the simulation model used as a tool for marketing may exchange accuracy for fast operation, the results will be accurate enough to give an idea of the usefulness of the product. And as all the simulations are done with the same inaccuracies, the comparisons will remain realistic.

A model of an entire industrial process can also be used as a tool for marketing. This type of model would offer even less accurate simulation of the product itself, but would take into account the process it is a part of. Again, simulations with several sets of parameters depicting different situations would offer comparable sets of data, this time from the process point of view. This type of a model would not necessarily benefit from detailed graphics engine. Instead it could be run quickly to give clear results and so be used to show the customer the financial benefits even more clearly.

These two types of models could be used in the same sales event to give the potential customer a multiple arguments in support of the purchase. With some additional programming the output data from both models could possibly be combined and displayed through single interface, creating a marketing tool. The ability to use the models using only a laptop computer and possibly a game controller would eliminate the need to bring the customer to a test facility to experiment with the actual product, thereby saving everyone’s time. In the marketing event the use of the models should be made as transparent as possible, allowing the customer to see the parameterization process and experiment with the models as they please in order to give credibility to the simulations.

Analysis of the use data of a product could be used to direct the marketing of additional features to the user. The analysis could reveal uses of the product that could benefit from additional features already sold by the manufacturer, and the marketing simulators could then be used as an argumentation tool to show the client how they could further enhance the use of the product by buying extra features. For some products, these additional features can be coded into their control systems and locked, so that they are not available if the client does not pay for them. Data analysis would reveal their need and simulation would provide further arguments to support the client’s decision of purchase. The features could even be unlocked remotely, making them a sort of a downloadable content for machines. As mentioned before, the models themselves could be sold, given compatibility with the client’s own analysis environment.

3.4 Installation process enhancement using simulation

Often the product requires parameterization during its installation. Its control system needs to be configured based on its operating conditions. Such parameterization often needs experimenting with the actual product. This could be done beforehand using simulation to obtain the parameters needed. For example, a model could be given certain boundary values, such as desired speed and acceleration with a certain mass being moved. The model would then parameterize its PLC values to fulfill those initial values and output the optimal configuration of the PLC. Most likely the simulation results would not correspond to the reality perfectly, but the use of simulation would limit the range of parameter values and thereby make the actual process of on-site product activation faster. The production planning data of the process the product will be a part of would also be taken into account here, giving a source for the boundary values used in the control configuration simulation runs.

For the purposes of enhancing the product development, the installation phase operations create data on how the product behaves when it is new, how easy it is to configure it and how quickly the installation is done. If the mechanics installing the product log events to a format usable by the product development team, the problems encountered during the installation can be recorded and used for further product development. On the other hand, if there are models of the location the product will be installed in and the product itself, it would be possible to create an installation simulator that would give the mechanics an idea of possible difficulties they might face. Quite like the simulation of the feasibility of assembly, only now the assembly refers to the entire factory or plant.

3.5 Training simulator applications

Recent developments in the use of simulators as training tools have led to virtual machine laboratories, which utilize the models to give an accurate picture of the inner workings of the product during its operation. They can also be used to demonstrate the events leading to faults and breakages and to train maintenance personnel in detecting these faults.

Better parameterization and the easy availability of machine specific data would enable the trainees to train with simulators based on the actual machines they are going to operate or maintain. This also means that the training simulator and the fault detection model are actually very close to each other. Training simulators can also be used to collect data for the product development process (Brunsmann, Wilkes, Brocks 2011).

3.6 Condition monitoring applications

Condition monitoring can be performed using a model of the product. Measurement data from the product can be used to make predictions concerning the future behavior of the product. If the model is accurate enough and can parameterized and verified based on measurement data from the machine, it could replace some sensors on the machine. That is, if the input and the output of the system, for example control command and speed of an actuator can measured and used as parameters for the model, the simulation can give rather accurate results on other properties of the actuator and be used to detect faults. Sensors measuring heat, vibration or acoustical behavior may in some cases be replaced by simulation models. (Ghafari 2010)

Improving prognostics in order to gain a better view of whether or not the monitored machine will remain in operation until the next planned shutdown is a future interest in maintenance management (Huovinen 2010). Condition predictions can be used to plan the maintenance schedule of the machine. Simulation based on recorded control and measurement data from the machine as well as machine specific parameters gives more accurate results than calculations based on generic mathematical models of breakdowns or safe working period predictions. This data can then be used to create a maintenance schedule for the individual machine. More importantly, if there is measurement data available, the schedule can be controlled based on the actual condition of the machine and the predicted outcomes of its situation.

3.7 Fault detection applications

Model based fault detection can be done by running simulations with parameters gained from measurements made during fault situations. The results can then be compared to simulation results based on nominal operation. A model can be programmed to parameterize itself so that the simulation results correspond given values. If the model is given two sets of values, one based on normal operation and another based on the fault situation, the differences in the automatic parameterization processes will reveal the location of the fault. It is also possible to examine the chain of events leading to the fault situation. To save computing power and given that there is enough measurement data available, this process could be conducted several times, first with a less accurate model of the entire product and then with more detailed models of the sub-component that the first model has indicated as the source of the fault. What is measured and what output data from a model can be trusted should be considered from fault detection point of view.

Neural networks have also been researched as a method of quantitative analysis. The problem of these history-based methods is that they cannot react to new situations, faults that have not been encountered in the process history data (Huovinen 2010). An analytical model of a machine could be used to generate sets of data for the neural networks and classifiers to learn from. The historical data could be generated with a model instead of the actual system. This way the speed of the analytical simulation would not be an issue and the classifiers would not be dependent on historical events only. The analytical model could be utilized in other applications as well.

Simulation cannot be depended on to give completely accurate results. For example a repair crew directed to a fault by simulation results must be prepared to face conditions other than the simulation predicts, but more detailed predictions on the fault situation would give a good idea where to start. If the chain of events leading to the fault situation can be deducted from the simulation and verified on site, the process provides the users of the product suggestions on how to avoid similar situations in the future.

Stored command data and the corresponding measurement data could be used to monitor the use of the device. A simulation of the device in operation could run based on the command data and the results compared to a simulation of an ideal work cycle. Taken to a condition monitoring level, differences in strains and stresses could be compared and if they would cross certain thresholds, the user could be notified and informed that the device is being used in a way that seriously shortens its maintenance period.

3.8 Augmenting technical support

Several companies offer support services for their products. A real time simulation model of the product could be used as a tool for the support personnel. A dynamic model of the product would give the support person the ability to examine the present situation of the product and test possible solutions through simulation. This type of model should be accurate enough to predict real life situations in the realm of physics. An important requirement is the quick parameterization of the model based on the actual product being examined.

The environment of the product would also have to be taken into account. This means collecting measurement data from the product, recording its control data and data from its environment and transmitting these data to the support personnel. A process model could possibly be used in conjunction with the physics model in some cases.

3.9 Uses for simulation in the end-of-life phase

The end of life of a product is a major service opportunity. The product must be removed from the site of its operation and recycled. If the data from its preceding life cycle is available, analysis of this could point out which parts can be reused and which must be scrapped.

Condition monitoring simulation would also give an idea as to when the end of life occurs and give the user of a product time to replace the product without costly pauses in production or other use. Combining process design simulations with condition monitoring simulations would give the ability to add the end-of-life of a product as a part of the operation of the client's industrial process.

4. MODELING THE LIFTING DEVICE

The product chosen to be modeled as a practical example for this thesis is a lifting device with a hoist mechanism and a rope and hook used for lifting. This type of configuration is found in many lifting devices, such as overhead cranes, gantry cranes, tower cranes, telescopic mobile cranes, jib cranes and deck cranes. Some examples of lifting devices are shown in figure 4.1.

Figure 4.1. *Lifting devices, clockwise from the top left: an overhead crane, gantry cranes, quay cranes and transloading cranes (Konecranes 2014; Kalmar 2014; MacGrecor 2014).*

The devices shown in figure 4.1. all share similar components and basic functionalities, but represent only a fraction of the lifting device types that utilize ropes and hoists in their operation. Due to the confidential nature of the details of the device, the description of the model is purposefully left vague. The important aspects of the model are described, but the type of the device is intentionally left unclear. However, since many maintenance significant components and physical phenomena are common to many types of lifting devices, simulation models of different devices can be though to generate data similar to the results presented below.

4.1 The structure and operation of the device

The lifting device features five components that are of interest when modeling its action. These are a moving beam, a vehicle with wheels, the hoist mechanism itself, the load being lifted and the control system.

There are several structural beams in the device. There are also wheels driven by electric motors, electric brakes, limit switches and end stop buffers. The hoist mechanism consists of a rope drum, reeving wheels, hoisting motor, gearbox, a brake, and limit switch which reacts to the movement of the rope. The load being lifted is included in the items to be modeled, because its attributes affect the way the rope and the hoist act. This is due to the aerodynamic qualities of the load having a small effect on the swinging motion of the load caused by the device's movements as well as the mass of the load affecting the hoisting mechanism, which in turn distributes these effects to the rest of the device. The control system, comprising of a PLC and inverters, operates the device. The automated functions of the device are included as a part of the PLC's programming.

The device is operated by the user via a controller unit. The controller unit sends speed and hoisting requests to the PLC, which either generates speed control ramps for the inverters or passes the requests to the inverters which generate the ramps. These ramps are used to control the electric motors of the device. The PLC also receives data from the limit switches and various sensors and controls the operations of the motors through the ramps in a preprogrammed way designed to enhance operator safety and optimize the life cycle of the device. The automated functions, when switched on, may take over some of the PLC functions and generate control ramps to fulfill their operating goals.

The operating environment of the device is not taken into account, although it does impact the device's operation in reality. Temperature changes, moisture from the air condensed on the tracks, air currents affecting the load being lifted and dirt particles in the air all affect the device's operation. Generally speaking these impacts are either small or predictable and are therefore omitted on this level of modeling. Some devices operate in more extreme conditions, where for example the temperature alterations within a work cycle can be very high or weather conditions can have significant effects. A model should be able to take such things into account, or else the simulation results must be interpreted with the omission in mind.

4.2 Simulation model of the device

The model consists of the five top level models mentioned above and the submodels required to simulate the important functions and behaviors of the device. The modeling strategy is to build the model from component level submodels which can be replaced with more accurate versions depending on the needs of the user. The model built is the basic structure for many different uses. The components and qualities needed for the purposes of this thesis are given more detailed attention, while the rest are left less accurate and thereby requiring less computing power. This also means there are some elements and connections which do not have a function at the current stage of modeling, but make it possible to add features later. For the sake of modularity the model is built using physical modeling. That means that the structure and the interactions within the model correspond to the physical structure of the real life device and that the components interact with the others only through the transmission of interactions which have real life physical counterparts. This enables any submodel to be replaced without any knowledge of how the submodel works. The only consideration should be the realistic enough physical interactions. A downside of this modeling strategy is the inherent high computing power demand of the model, and the algebraic loops easily created in it.

The model was built using MATLAB Simulink. Some of the component submodels were created with AMESim and imported to the Simulink environment as black box models. The solver used in the simulation runs was ode45tb, chosen for its ability to handle the stiff equations created by the AMESim submodels. The downside of this is that the simulations cannot be run reliably in real time; they are always discrete. Also worth noting is that AMESim is a physical simulation software and so deals with physical variables with corresponding unit values. Simulink on the other hand is computing software which operates with numerical values. Therefore conversions from unit to numerical and vice versa are required within the AMESim submodels.

The model building began with very basic top level structure, in other words the process was executed as top down-modeling. Since many of the component models could be reused in different locations, most of them were built and tested using the vehicle model. A visualization tool was found, a 3D representation of the device. This helped in clarifying the functionality of the submodels during the first phases of the model building. When the basic system model was ready, more complex dynamics were introduced and more components were added. A joystick was connected through the Simulink Joystick input block as a means to control the model for quick test simulations and verifications. The model was thus partially verified with a human-in-the-loop approach. Even more complex actuator models were included. Finally the simplified versions of the control systems were created, tested and included in the model. The complete model includes the four submodels and the PLC model. The submodels communicate through the transmission of force, acceleration or measurement data to the control elements.

4.3 Descriptions of the physics models

The modeling of the physical aspects of the device, as opposed to its actuators and control systems, are described next. Most of these models are used to simulate several different components in the device, their parameters changed to reflect the differences in the components.

4.3.1 Description of the wheel model

The wheel model is used to simulate any of the devices wheels. Figure 4.2 shows the Simulink block diagram of the wheel model.

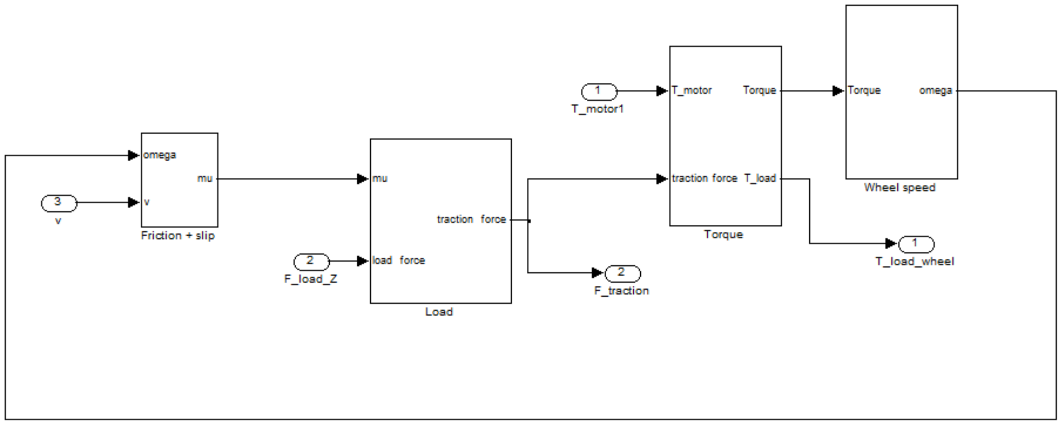


Figure 4.2. *The Simulink block diagram presentation of the wheel model.*

As seen in figure 4.2, the model calculates the total torque causing the movement of the wheel by subtracting the traction torque from the torque provided by the motor model. This total torque is then divided by the moment of inertia of the wheel and the result goes through an integrator, giving the angular speed of the wheel. This is used to calculate the speed of the wheel, which in turn is used to calculate the slip factor λ using the equation

$$\lambda = \frac{\omega_w - \omega_v}{\omega}, \omega \neq 0 \quad (1)$$

where ω_v is the vehicle angular velocity of the wheel, equal to the linear vehicle velocity v, divided by the radius of the wheel r. The variable ω is defined as

$$\omega = \max(\omega_w, \omega_v) \quad (2)$$

which is the maximum of the vehicle angular velocity and wheel angular velocity (Ming 1997). The vehicle speed v is gained from the vehicle dynamics block. The slip factor is used to calculate the adhesion coefficient μ in the equation

$$\mu(\lambda) = \frac{2\mu_p\lambda_p\lambda}{\lambda_p^2+\lambda^2} \quad (3)$$

where μ_p and λ_p are the peak values of the adhesion coefficient and the wheel slip curves, respectively. These curves depend on the conditions of surface the wheel is rolling on. (Ming 1997; Tamberg 2011)

Load force multiplied by μ gives the traction force and, multiplied by the wheel radius, the traction torque, which is subtracted from the torque given by the motor model.

In the case of an idle wheel, i.e. a wheel with no motor connected, the torque subtraction is replaced by comparison of the pull force the wheel axle is subjected to and the traction force calculated in the aforementioned manner. (Ming 1997; Tamberg 2011)

The vehicle speed needed in the slip calculations is calculated in the vehicle dynamics block using Newton's second law. The traction forces from the wheel models, created by the motor or required by the pulling of an idle wheel and the lateral load forces created by possible bending of the tracks are added up to calculate the total lateral traction force affecting the vehicle. A force created in a situation of collision with the end stop model is subtracted from this force. The total mass required by Newton's second law is calculated by multiplying the load force affecting the vehicle by the gravitational acceleration and adding the result to the mass of the vehicle itself. This way the submodel requires only the load force as input, other masses such as the load mass and vehicle masses are transmitted through force, adhering to the modeling principle of physical modeling and realistic interactions between submodels. With the total mass and the total force known, the acceleration of the vehicle can be calculated. Two consecutive integrators applied to the result give the vehicle speed and location, respectively. (Ming 1997; Tamberg 2011)

4.3.2 Descriptions of the dynamics models

The dynamics block is used to model the dynamic behavior of the device's structure. In this thesis simple deflection and skew models were included, but it would be easy to add more dynamics blocks and trace their effects on the wheels or the load distributions on the vehicle.

The beam deflection model calculates the deflection and the deflection angle caused by the masses of device components and the mass of the load being lifted. The calculation assumes the mass of the beam to cause an evenly distributed force field and the mass of the vehicle with the load to cause a force to single point. The location of the vehicle on the beam is taken into account. The following equations are used to calculate the deflection angle β and the amount of deflection along the Z-axis.

$$v_{mg}(x) = \frac{F_{load}L^2}{6EI}\left[\frac{c_{end}b_{end}}{L^2}(L + b_{end})\frac{x}{L} - b_{end}\left(\frac{x}{L}\right)^3 + \frac{(x-c_{end})^3}{L^2}\right] \quad (4)$$

$$v_q(x) = \frac{q_0L^4}{24EI}\left[\frac{x}{L} - 2\left(\frac{x}{L}\right)^3 + \left(\frac{x}{L}\right)^4\right] \quad (5)$$

$$v'_{mg} = \frac{F_{load}c_{end}b_{end}(L+b_{end})}{6LEI} \quad (6)$$

$$v'_q = \frac{q_0L^3}{24EI} \quad (7)$$

Where F_{load} is the force caused by the mass of the load, L is the length of the beam, c_{end} is the distance from one end of the beam and b_{end} from the other end, q_0 is the force field affecting the beam, E is the modulus of elasticity of the beam and I is the area moment of inertia of the beam. Equations 4 and 5 are used to calculate the amount of deflection in the Z-direction caused by the total mass of the vehicle and the load and by the force field generated by the beam's own mass, respectively. The results are summed to give the total deflection. Equations 6 and 7 are used to calculate the deflection angle of the beam. Derived from these equations are equations for the deflection angle in both ends of the beam. A switch is used to select the appropriate angle depending on which end of the beam the vehicle is closest to. The results are again summed to give the total effect on the deflection angle. (Salmi, Pajunen 2010)

The skew model tackles the situation where one of wheels of a vehicle moves faster or farther than the other, causing the vehicle to skew. The block diagram of the model is depicted in figure 4.3.

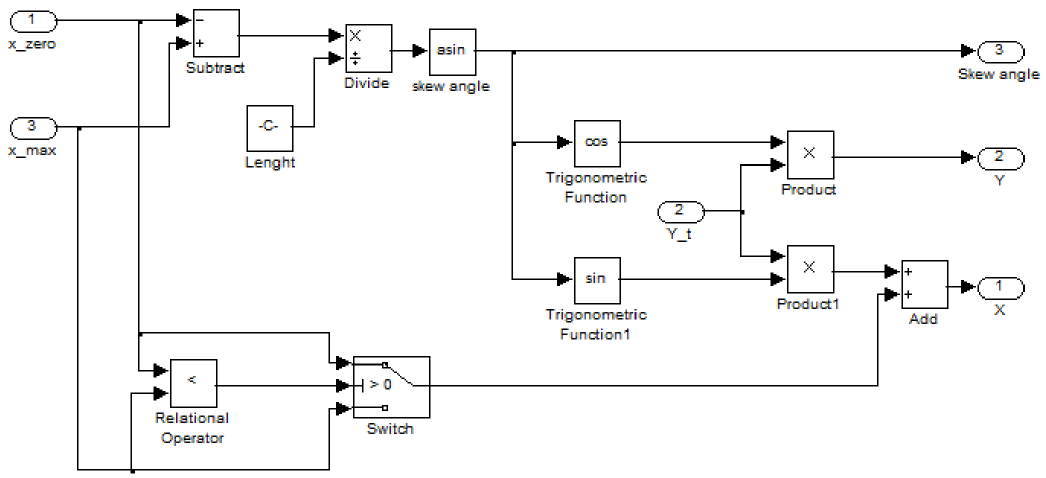


Figure 4.3. *The Simulink block diagram presentation of the skew model.*

As can be seen in figure 4.3., the model takes into account two wheel sets, comparing their longitudinal coordinates and uses this difference and the vehicle width to calculate the skew angle α_{skew}. The equations for the skew angle calculation are presented below.

$$\alpha_{skew} = \arcsin(\frac{x_{right\ hand\ end} - x_{left\ hand\ end}}{l_{vehicle\ width}}) \quad (8)$$

$$y = y_{vehicle} * \cos \alpha_{skew} \quad (9)$$

$$x = x_{vehicle} * \sin \alpha_{skew} \quad (10)$$

The angle is calculated using equation 8, where $l_{vehicle\ width}$ is the width of the vehicle. The result is used to calculate the effect on the x and y coordinates of the hoist ropes with equations 9 and 10. The skew angle also has an effect on the x,y-direction acceleration of the hoist ropes, but the effect is so small it is calculated only as a mean value of the vehicle wheel set accelerations by another submodel.

The beam deflecting under the weight of the vehicle and load causes the beam to form a downhill as the vehicle moves towards the center of the beam and an uphill as it moves away from the center. The deflection angle effects block calculates the y-direction force affecting the vehicle based on its location, the direction of its movement and the load force affecting it. The resulting force will either accelerate or decelerate the vehicle movement. The force itself is determined with equation

$$F_{angle\ effects} = F_{load} * \sin\beta * h_{uphill} \tag{11}$$

Where F_{load} is the load force affecting the vehicle, β is the beam bend angle and h_{uphill} is a factor of -1 or 1, which makes the load force either an accelerating or a decelerating force. The uphill factor is determined by a series of Simulink logic operators. First a relational operator compares the vehicle's position with the location of the center of the beam. At the same time another relational operator compares the vehicle's speed to zero in order to find out whether it is negative or positive, which in effect means the direction the vehicle is travelling. Then a logical operator XOR compares the truth values of the vehicle's position and the direction of speed, giving a one if the vehicle is moving towards the center and a zero if the vehicle is moving away from the center. This value controls a switch, which will choose a value of 1 for the uphill factor if the vehicle is moving downhill and the load force is therefore accelerating it and -1 if it is moving uphill and force is decelerating it.

4.3.3 Description of the end stop model

The device features end stop buffers for the vehicle. These are modeled using AMESim black boxes. AMESim provides simple elastic contact with no states (LSTP00A) model, which uses a spring model and a damping model to simulate the effects of a buffer. The model calculates elastic effects occurring during contact between two bodies in one-dimensional linear motion. The gap between the two bodies is computed as

$$gap = gap_0 - x_1 - x_2 \tag{12}$$

where x_1 is the displacement of one body and x_2 the displacement of the other and gap_0 is the gap when both displacements are zero. The penetration value and the velocities of the bodies are then calculated as

$$pen = -gap \tag{13}$$

$$\mathrm{der}(pen) = v_1 + v_2 \tag{14}$$

where *pen* is the value of penetration and v_1 and v_2 are the velocities of the two bodies, respectively. A positive value of pen means contact. In that case, the contact force is calculated with the equation

$$f = \begin{cases} kx + r_{visc}v & if\ x \geq 0 \\ 0 & if\ x < 0 \end{cases} \tag{15}$$

where x is the relative displacement between the bodies, k is the contact stiffness and r_{visc} is the contact viscous friction. In order to avoid a step change in the force when the displacement is zero, a damping coefficient is used

$$r(1 - \exp(\frac{-3x}{e})) \tag{16}$$

where e is the deformation of the body required to reach 95 % of the contact viscous friction. (LMS ImagineLab AMESim 2012) The submodel AMESim block diagram is represented in figure 4.4.

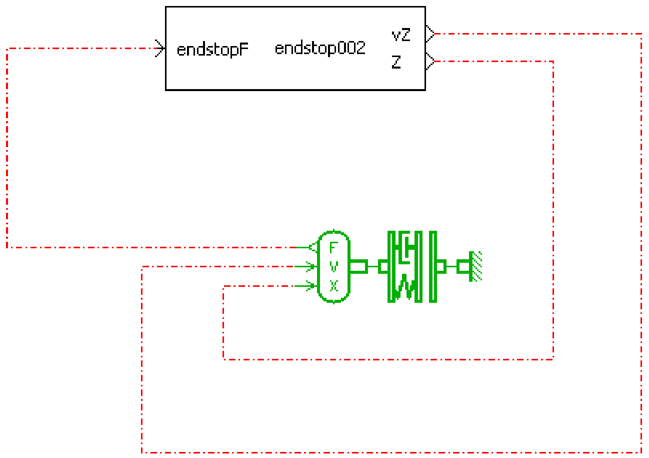


Figure 4.4. *The AMESim block diagram presentation of the end stop model. The blocks are described in the appendix.*

As can be seen in figure 4.4., the elastic contact model is coupled with a signal-to-unit converter, which converts the speed and location data coming from the Simulink model into their respective units and converts the force value given by the elastic contact model into a signal which can be routed to the Simulink model.

4.3.4 Description of the pendulum model

The swaying of the load being lifted is very real and important issue with all lifting devices. That is why it’s important to model the pendulum effect of the load. The pendulum model calculates the load sway in the x- and y-directions separately, so the same equations are used for both directions. Based on the directional acceleration, load mass and the pendulum length, the uncoiling of the rope, the model calculates the gravitational force, the acceleration force and the air resistance, also known as drag. For the drag calculation, the drag coefficient and the corresponding cross section area of the load are also needed. The masses, areas and drag coefficients of the load and the hook are summed together before the actual pendulum calculations. The pendulum model block diagram is shown in figure 4.5.

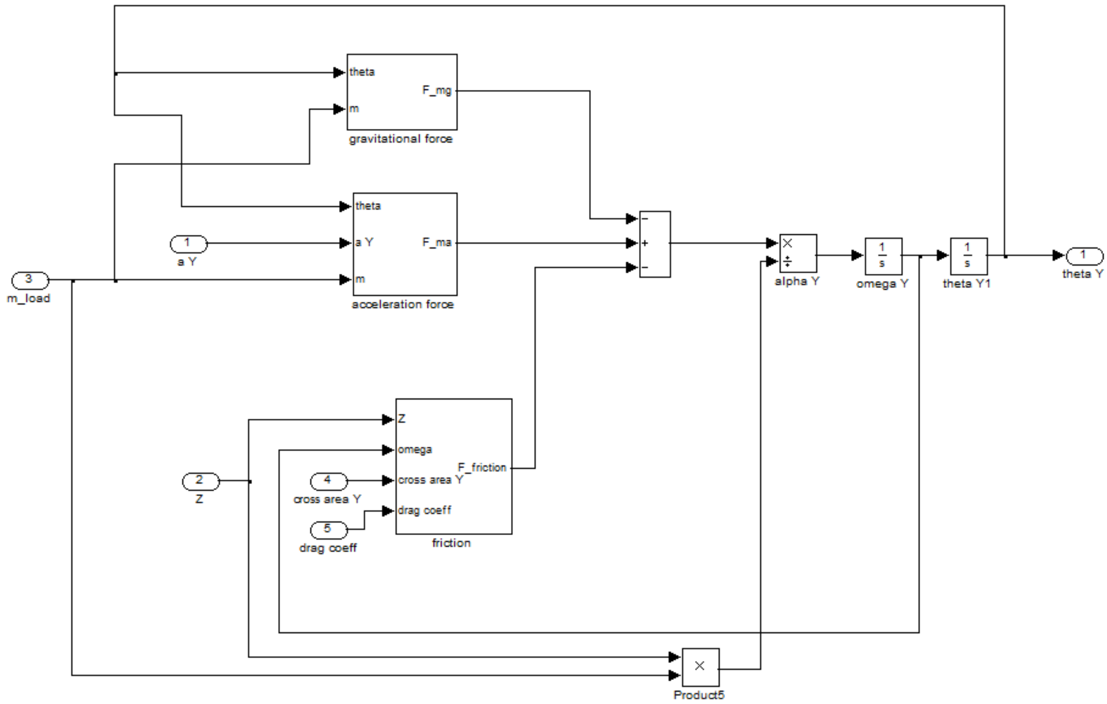


Figure 4.5. *The Simulink block diagram presentation of the pendulum model.*

Figure 4.5. shows the three elements of the pendulum movement, the acceleration of the pivot point, the gravitational effect and the resisting forces. While a theoretical pendulum's motion is not affected by the mass, formulating the equations through force allows the addition of drag and in the future also frictions in the calculation. The equations for the three elements of the pendulum are as follows:

$$F_{mg} = m_{load}g * \sin\theta \quad (17)$$

$$F_{ma} = m_{load}a * \cos\theta \quad (18)$$

Where θ is the angle of the pendulum, a is the acceleration of the pendulum pivot point in the vehicle and m_{load} is the mass of the load attached to the rope. The drag of the load is calculated with the equation

$$F_{drag} = \frac{1}{2}\rho(z\omega_{pendulum})^2 AC \quad (19)$$

Where ρ is air density, C is a drag coefficient depending on the shape and size of the load and A is the area of the load's side perpendicular to the pendulum direction, z is the rope length and $\omega_{pendulum}$ is the angular velocity of the pendulum motion. (Lupton 2009)

The drag force acts as a motion resisting force, which is then subtracted from the motion creating acceleration force. The gravitational force is also subtracted from this to get the total force driving the pendulum. This force is divided by the load mass times the rope length to obtain the angular acceleration, which is routed through two integrators to obtain the angular speed $\omega_{pendulum}$ and the angle θ, respectively. These two angular values are required in some of the calculations detailed above. The pendulum angle θ is also the output of the pendulum model. (Benn et al. 2004)

4.3.5 Descriptions of the load distribution models

The load forces are distributed to the wheels based on the location of the vehicle and the pendulum effects. Since the submodels transmit forces to each other, it is important to calculate the force distributions. Figure 4.6. shows the load force distribution model block diagram for the vehicle.

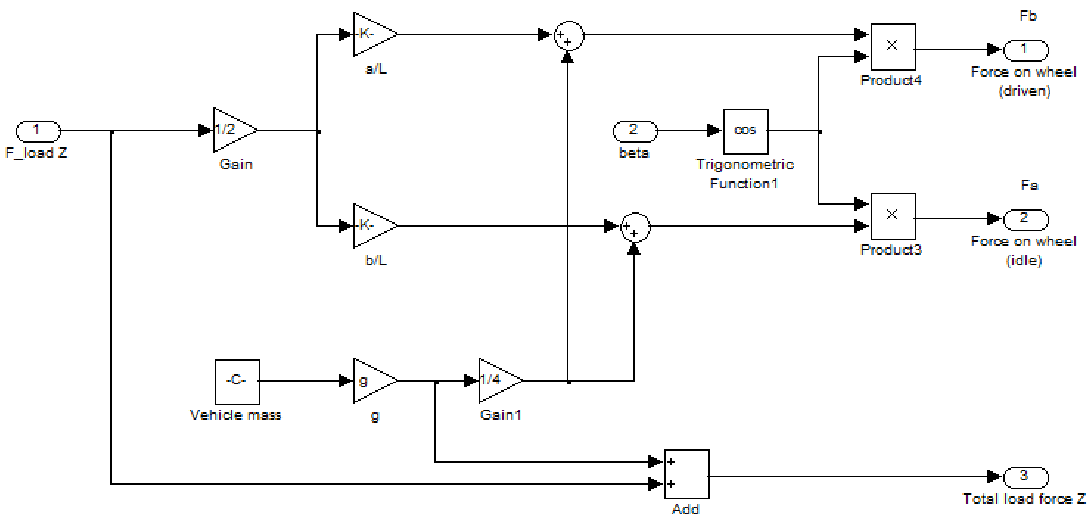


Figure 4.6. *The Simulink block diagram presentation of the vehicle load force distribution model.*

The block diagram in figure 4.6. shows how the load affecting one of the vehicle's wheels is calculated and transmitted to the wheel model. The calculation takes into account the distance of the vehicle's wheels from the point where the hoisting mechanism is attached; the vehicle's own mass, divided equally to all the four wheels and angle of the beam on which the vehicle is moving. This angle is caused by the beam's deflection. The equation is as follows:

$$F_a = \left(\frac{b_{idle\,wheel}}{l_{vehicle\ lenght}} * \frac{1}{2} * F_{load} + \frac{1}{4} m_{vehicle} g\right) cos\beta \qquad (20)$$

where $b_{idle\ wheel}$ is the distance of the wheel from the hoist mechanism, $l_{vehicle}$ is the distance between the wheel axles, F_{load} is the force created by the load being lifted, $m_{vehicle}$ is the mass of the vehicle and β is the beam deflection angle. The total vertical force affecting the beam is also calculated, so that the vehicle mass is transmitted to the beam model as a force. However, this calculation makes the simplification of assuming that the vehicle acts on the beam as single point force instead of transmitting each wheel's force on the beam.

The beam load distribution model works the same way, but takes also into account the location of the vehicle on the beam and leaves out the bend angle effects. The vehicle load force is transmitted to the beam as a point force. The effect of the vehicle location is calculated using equation 21, then the beam's own mass is divided evenly for its eight connection points and the submodel outputs forces affecting these connection points of the beam, giving the following equation.

$$F_a = \frac{1}{2}\left(\frac{L - y_{vehicle}}{L} * \frac{1}{2} F_{total\ load\ on\ beam}\right) + \frac{1}{8} m_{beam} g \qquad (21)$$

where L is the beam length, $y_{vehicle}$ is the location of the vehicle on the beam, $F_{total\ load\ on\ beam}$ is the sum of the load forces affecting the beam vertically and m_{beam} is the mass of the beam.

The pendulum load distribution model calculates the force affecting the rope. The angle θ_{xy} is the angle of the pendulum compared to the perpendicular, in other words a barrel coordinate angle that does not tell the direction of the pendulum's swing, only its deviation from the vertical. The angle is calculated using the equation

$$\theta_{xy} = \frac{\pi}{2} - \arcsin(\sin\left(\frac{\pi}{2} - \theta_y\right)\sin\left(\frac{\pi}{2} - \theta_x\right)) \qquad (22)$$

where θ_x and θ_y are the swing angles of pendulum in x- and y-directions, respectively. The load force on the rope is then calculated using the equation

$$F_{load\ z} = cos^2\theta_{xy} m_{load} g \qquad (23)$$

The model does not take into account forces perpendicular to the movement directions of its components.

4.4 Descriptions of the actuator models

The models of the actuators are described below. The motor, brake and gear models are used in several instances, again with changed parameters.

4.4.1 Description of the electric motor model

The motor is modeled with AMESim and added to the Simulink model using the black box feature. A signal to torque converter (TORQC) is transmitting torque to a rotary load with friction (RL04). This in turn transmits a revolutions-per-minute value to a rotary Coulomb and stiction friction represented by a reset integrator model (FR1R0010), which is used to simulate the brake.

The reset integrator model models the effects of stiction friction and Coulombic friction, but no inertia. There is a relative displacement value, which starts at zero with no friction force created. If this displacement value changes, a stiction force is created. If the displacement value crosses a threshold, a sliding movement is happening and the friction force created is the Coulomb friction force. Stiction is calculated with the following equations:

$$K_{stick} = \frac{f_{stick}}{\mathrm{d}x} \tag{24}$$

$$F_{frict} = K_{stick}x + B_{rel}V_{rel} \tag{25}$$

where K_{stick} is a contact stiffness value depending on the maximum stiction friction force f_{stick} and the displacement threshold dx. The friction force F_{frict} is then calculated based on this contact stiffness value and the damping coefficient B_{rel} which is used to avoid vibrations when the solids stick together and depends on the relative velocity between the two bodies V_{rel}. In the case of sliding, the friction force is calculated with the following equation:

$$F_{frict} = f_{slip}\,\mathrm{sign}(V_{rel}) \tag{26}$$

where f_{slip} is the Coulomb friction between the moving bodies. There is also an input signal ranging from 0 to 1 that determines the fraction of the maximum value of friction force that the model outputs. This is used to control the amount of braking torque. (LMS ImagineLab AMESim 2012)

The total torque transmitted to the wheel model is calculated by subtracting the input value of the torque from the wheel model from the torque from the converter. The torque from the brake is also subtracted from this value to gain the total torque. The control signal from the PLC model to the torque converter is multiplied by a gain (GA00), turning the -1 – 1 control signal into the torque value. Gearboxes in the travelling motors are simple gear ratio gains in the Simulink model. The AMESim block diagram is represented in figure 4.7.

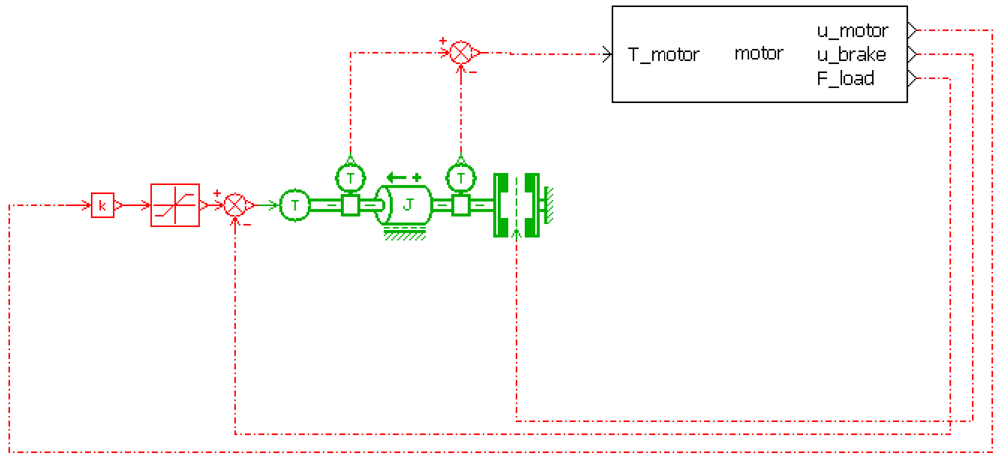


Figure 4.7. *The AMESim block diagram presentation of the motor model. The blocks are described in the appendix.*

Figure 4.7. shows the block diagram of the electric motor model. Featured are torque-to- signal-converters, inertia and brake models. Again, a unit-to-signal conversion is required for the Simulink interface.

4.4.2 Descriptions of the hoist model and rope models

The hoist and rope models are also created in AMESim and added as a black box, which includes the hoisting motor, brake, winch and rope. Control command value from Simulink is multiplied by gain and fed through a signal-to-torque converter to obtain the motor torque. The torque converter and the brake model are connected with a rotary link (TILI0C) to obtain the total torque affecting the winch. This torque is connected to a rotary load with friction, which transmits it to the winch model (WINCH01). The winch model is connected to a rope (ROP0001) and rope-end (REND001) models. The rope end model in turn connects to a two-port mass model (MAS002). The second port of the mass model is connected to force converter (FORC) which converts the load force signal coming from Simulink to a force affecting the mass and the rope. The torque at the brake as well as the displacement and velocity of the mass at the end of the rope are sent to Simulink as output values. The hoisting gearbox is taken into account through parameterization and the rope reeving configuration is handled by a gain for the load mass in the Simulink model. The AMESim block diagram is shown in figure 4.8.

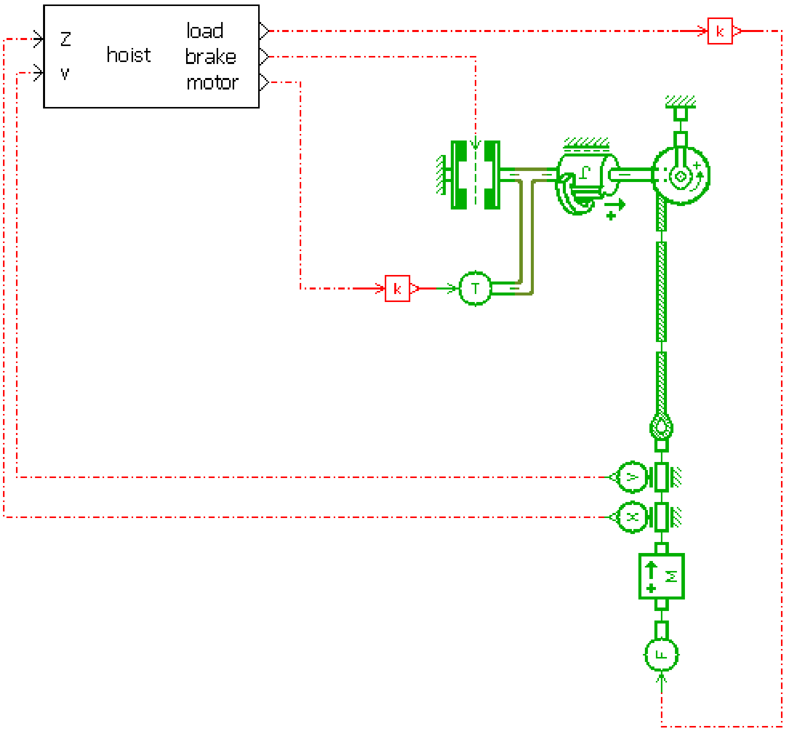


Figure 4.8. *The AMESim block diagram presentation of the hoist and rope model. The blocks are described in the appendix.*

Figure 4.8. shows that the hoist motor model has similar components to the electric motor model, but adds the winch and rope models as well as an inertia model with a limited turn capability to represent the length of the rope. The turning of the inertia model stops when the number of rotations has reached a limit that corresponds to the situation of the rope being fully extended or reeled in.

The rope model includes stiffness and internal viscous friction. The total length of the rope is calculated based on its initial length and uncoiling

$$l = l_0 + q_{mt1} + q_{mt2} + l_\Delta \qquad (27)$$

where l_0 is the initial length, l_Δ is the lengthening and q_{mt1} and q_{mt2} are uncoiling values at either end of the rope. The derivative of the length is calculated using the velocities of the rope ends:

$$\mathrm{d}l_\Delta = -v_{mt1} - v_{mt2} \qquad (28)$$

where v_{mt1} and v_{mt2} are the velocities. The total stiffness K and total viscous friction R of the rope are calculated using the rope's length but leaving out the lengthening.

$$K = \frac{n_r K_0}{l_0 + q_{mt1} + q_{mt2}} \qquad (29)$$

$$R = \frac{n_r R_{viso}}{l_0 + q_{mt1} + q_{mt2}} \tag{30}$$

In the equations n_r is the number of ropes bundled together, side by side, K_0 is the stiffness of unit length of rope and R_{vis0} is the viscous friction of unit length of rope. The force at the load end of the rope, f_{mt1}, is calculated using the equation

$$f_{mt1} = -f_{mtca} - R * \mathrm{d}l_{\Delta} \tag{31}$$

where f_{mtca} is force directed into the spring stiffness, R is total viscous friction of the rope and *da* is the derivative of the rope length. The force f_{mtca} is calculated by from its derivative using an integrator.

$$\mathrm{d}f_{mtca} = K * \mathrm{d}l_{\Delta} \tag{32}$$

The equation uses the total stiffness K and the derivative of the rope length to calculate the spring effect. (LMS ImagineLab AMESim 2012)

This approach turned out to demand extreme amounts of computing power due to the very small and relatively high frequency vibrations in the rope and the friction calculations needed to make the winch work realistically. For the purposes of the demonstrational cases, it was replaced with a very simple model which uses an integrator to turn the speed command from the PLC into the position of the hook. However, should the rope be an item of interest, the more accurate model could be used to examine its behavior. The simplified hoist model block diagram is shown in figure 4.9.

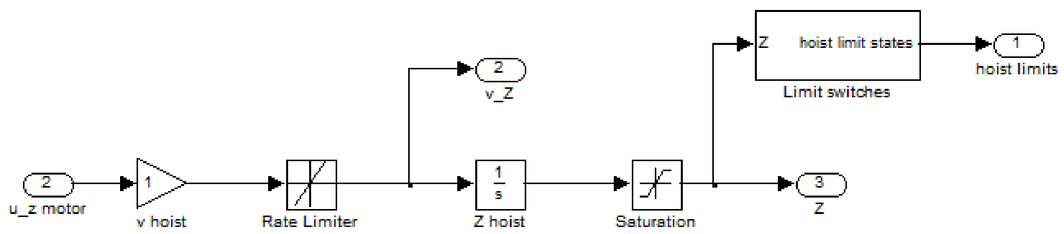


Figure 4.9. *The Simulink block diagram presentation of the simplified hoist model.*

As can be seen in figure 4.9., the simplified hoist model routes the command value from the PLC model through a rate limiter to give the hook movements a simple dynamical behavior and then through an integrator to turn the speed command into position value. This is routed through a saturation block representing the rope being either fully reeled in or extended, at which point the PLC also stops the commands. Also seen is the limit switch block, the content of which is described in the control model chapter.

4.5 Description of the control model

The actual device is controlled by a PLC controlling inverters. This part of the system is vastly simplified because of the scope of the thesis and the lack of information on the actual control logic. The automated functions are also executed in a simplified manner, facilitating the simulation of the actual device movements but omitting many of the configuration options available for these functions.

The PLC model includes a submodel for determining the actions caused by the limit switches being triggered, a submodel for engaging the brakes at predetermined situations and a submodel for a ramp generator. All of these models are very simple and have been created using logic blocks from the Simulink library, as their purpose is to simulate the actions caused by certain situations, not the actual inner workings of the real PLC-unit.

The rate limiter control model receives the speed request from the controller and the states of the limit switches. Limit switches are sensors. They are modeled to simply compare the position coordinate of the vehicle or load to a parameterized limit value and output zero if these conditions are not met and one if they are. This signal is used to control the PLC model.

If a slowdown area limit switch has been triggered and the speed request value is toward the corresponding end of the track, the speed request signal is routed through a slowdown ramp. If a stop limit switch has been triggered and the speed request value is toward the corresponding end of the track, the speed request signal is multiplied by zero to nullify the speed request.

The brake control model does the above described comparison between the direction of the speed request and the status of the stop limit switch and if the speed request is toward the end with a corresponding stop limit triggered, the brake control signal will activate. The brake control also compares the speed request value and the actual speed of the vehicle. If both values are zero, the brake control signal will activate to engage the standing brake function.

The ramp generator model provides the control commands for the motors. The model does not try to emulate an actual ramp generator, it merely chooses an appropriate ramp based on the situation of the vehicle and predetermined parameters. This is achieved by comparing the speed request value and the speed measurement value. If their directions are the same, the operator wants to accelerate and the speed request signal is routed through a fixed acceleration ramp. This also applies if the measured speed value is zero. If the directions are different, the user wants to decelerate and the signal is routed through a fixed deceleration ramp. There is also a motor braking control loop, which is engaged if the speed request signal is zero. In that case the speed measurement value has its sign reversed, is routed through a deceleration ramp and sent as a control value to the motor. This means the control value is proportionally inverse to the vehicle speed until the speed becomes zero. Finally there is a speed limit function, which cuts off the control signal if the speed measurement value exceeds the fixed speed limit parameter. This parameter is also found in the real PLC and is configured during the installation of the device.

There are two automated load handling functions included in the model. One of them reduces the pendulum motions of the load while the other guides the device automatically to a predetermined position.

4.6 Validation and verification of the model

In order to verify the functionality of the model a set of test simulation runs is made. There is little data available to compare the results with and some parts of the model are simplified. Therefore the verification can only be performed as a sort of a sanity check for the model, running simulations and judging the validity of the results based on what data is available and on common sense.

The main components to be tested are the wheel model with its slip factors, the beam deflection model, and the pendulum model. The entire model is tested for realistic accelerations and actuator functions. The real device adjusts its motor control ramps based on the load it is lifting. Since the control system is simplified, the load ramps have to be adjusted manually. These test runs are conducted with a heaviest recommended load mass attached to the hoist.

In the first verification run the vehicle is accelerated for 20 seconds, after which time the command for the forward movement ends. The vehicle will then stop its movements. Acceleration, brakes and wheel slips are monitored, as well as the pendulum motion of the load being lifted and the deflection of the structural beam. Figure 4.10. shows the command signals of the motors and the brakes, the resulting torques, as well as wheel slip factor of the driven wheel.

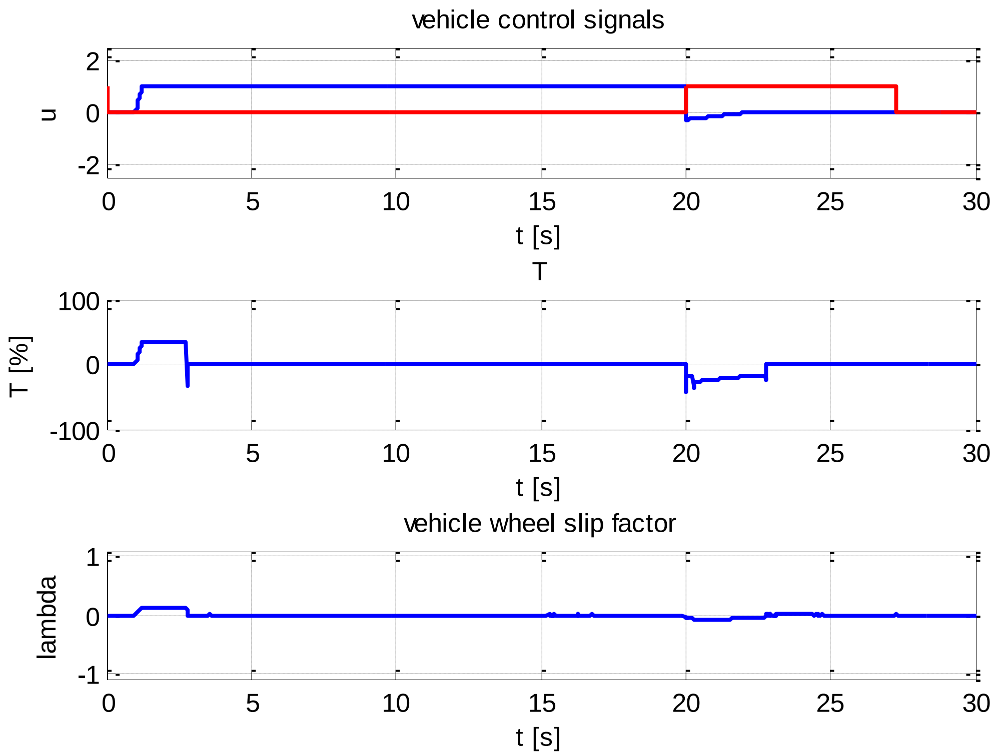


Figure 4.10. *Vehicle motor control and brake control signals and their effect on torque and wheel slip.*

In figure 4.10. the speed does not exceed 20 m/min, which is the limit for the vehicle. Accelerations can be seen to remain relatively low, which is explained by the large mass being moved. The motor torque rises to accelerate the vehicle. The brakes engage as the command signal ends and the brake torque can be seen in the torque graph, added to the motor torque slowing the vehicle down. The wheel slip of the driven wheel of the vehicle shows the initial slip during acceleration, the small slide during braking and the better hold characteristics during even speed. Figure 4.11. shows the vehicle acceleration, speed and position resulting from the torque and slip values.

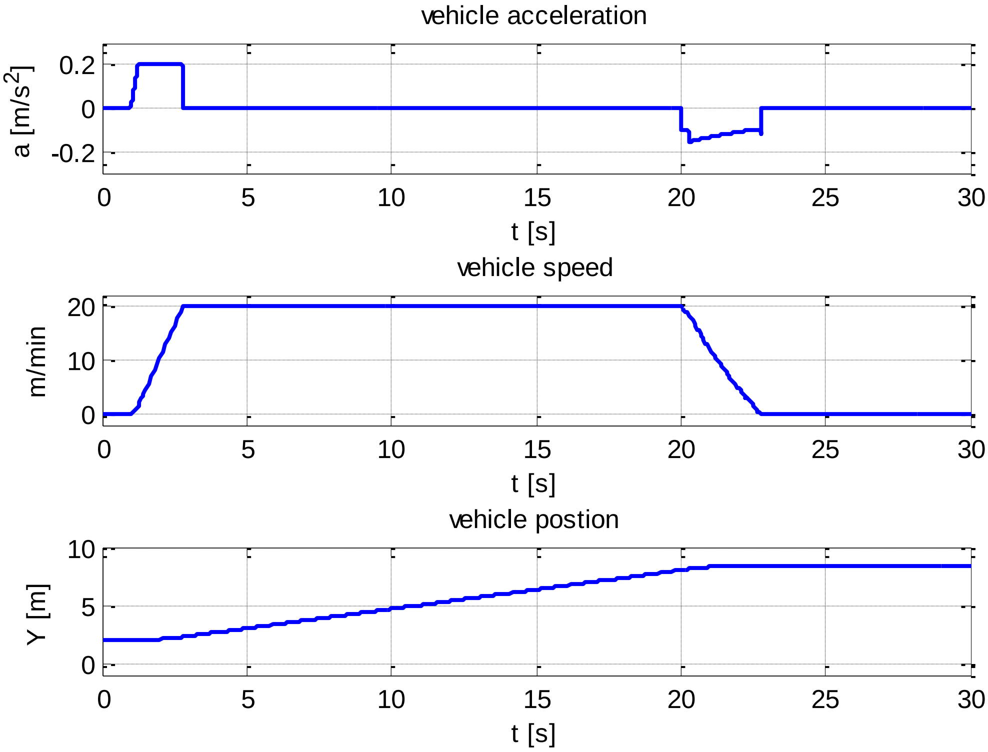


Figure 4.11. *Vehicle acceleration, speed and position.*

Figure 4.11. shows the vehicle speed rising during the acceleration until the set speed limit of 20 m/min is reached and then remaining steady until at twenty seconds the stop command is given. The speed then falls as the brakes step in. The vehicle movement is seen to be steady and it stops within an acceptable time after the stop command is given. Figure 4.12. presents the pendulum movement of the load caused by this vehicle operation, as well as the deflection caused in the structural beam.

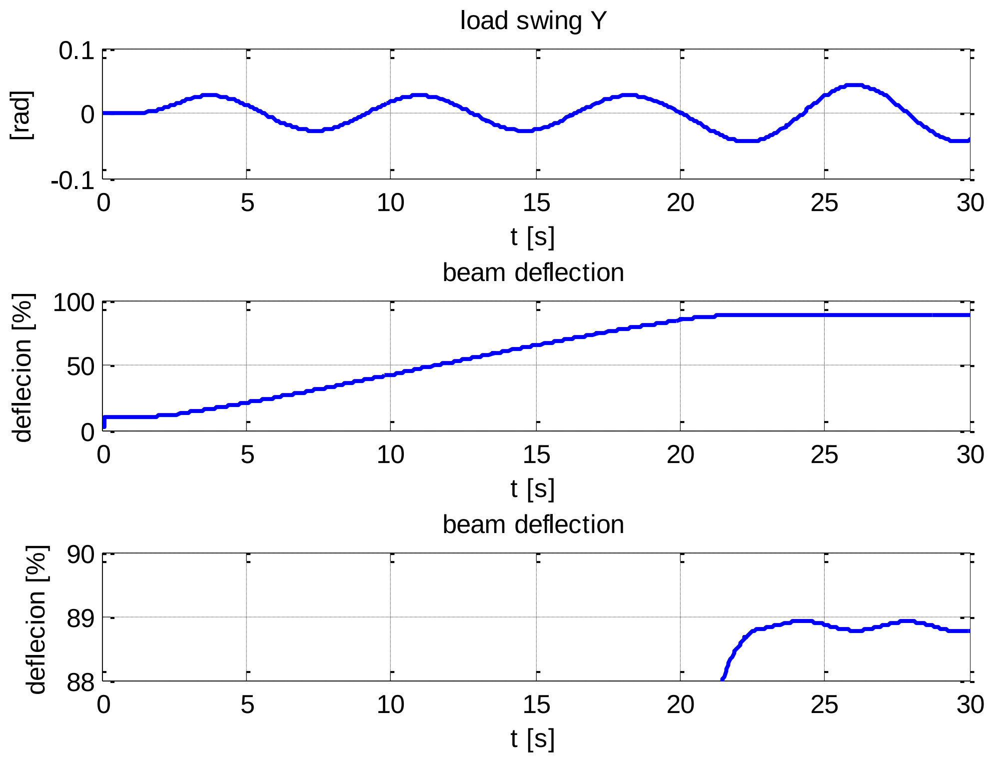


Figure 4.12. *Load swing, beam deflection and a closer look at the effect of load swing on the beam deflection.*

In figure 4.12., the pendulum is seen to act expectedly, responding to the stopping of the vehicle by transferring the kinetic energy of the system into the pendulum motion. It can also be seen that air resistance has little effect on the movement, as the large mass stores very large amounts of kinetic energy. The deflection of the beam can be seen to depend on both the position of the vehicle along the beam. The pendulum motion causes the vertical force on the beam to fluctuate, but these fluctuations are small compared to the effect of the vehicle's location on the beam. The last graph shows a closer look at the beam deflection after the vehicle has stopped moving, making this fluctuation visible. The largest amount of force caused by the swinging load on the beam occurs when the load is directly below the beam and all of the load force is transmitted vertically through the rope. The model reflects this phenomenon.

The operation of the simplified hoist model used during the service tool cases is demonstrated next. The control signal of the hoist is assumed to correspond to the speed of the hook and is integrated to gain the hook position. The slowdown limit areas are taken into account. A work cycle of load being lifted and lowered is shown in figure 4.13.

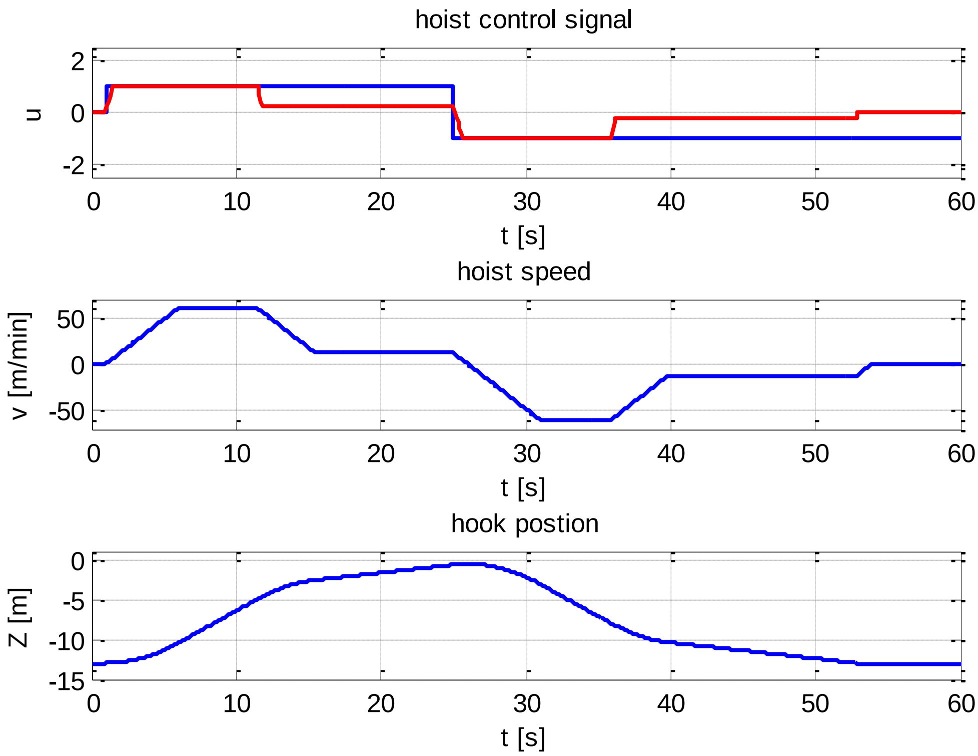


Figure 4.13. *Hoist control signal and the ramp based on it, hoist speed and hook position.*

Figure 4.13. shows the control signal of the hoist model and the command ramp generated by the PLC based on the said signal. In this simplified model the hoist speed is directly related to the command ramp. The speed is integrated to obtain the hook position. The effects of the slowdown areas triggered by limit switches near the maximum and minimum positions of the hook can be seen.

5. UTILIZING SIMULATION IN SMART SERVICES

In this chapter the model is used in service enhancement applications to demonstrate the possibilities of simulation as a tool for smart services. Five cases from different life cycle phases are demonstrated using the model described in chapter four. The cases are an installation tool, a maintenance planning tool, a use monitoring tool, a product development tool and finally a marketing scenario using the information created in the other cases. All the cases refine initial data into information, but the information also requires further development in order to reach full usefulness. This is discussed in chapter six.

5.1 Defining installation parameters

The model has been parameterized based on an actual lifting device. During the installation of the device, as it is delivered to the customer, the nominal speed parameter of the PLC controlling the vehicle motors is tuned so that the device's work cycle speed meets the customer's criteria. The properties of the load the device lifts are known. In the following simulations the idea is to obtain the best possible nominal speed PLC value through iteration. Assuming that the model is accurate enough, the values obtained should be close to the values required by the PLC of the real device and serve as a good starting point in its calibration during the installation phase.

The simulation run is made with a maximum allowed load and the desired operational speed of the vehicle is 20 m/min. Figure 5.1. shows the acceleration of the vehicle and the operational speeds the PLC allows it to reach during the runs of the calibration simulation.

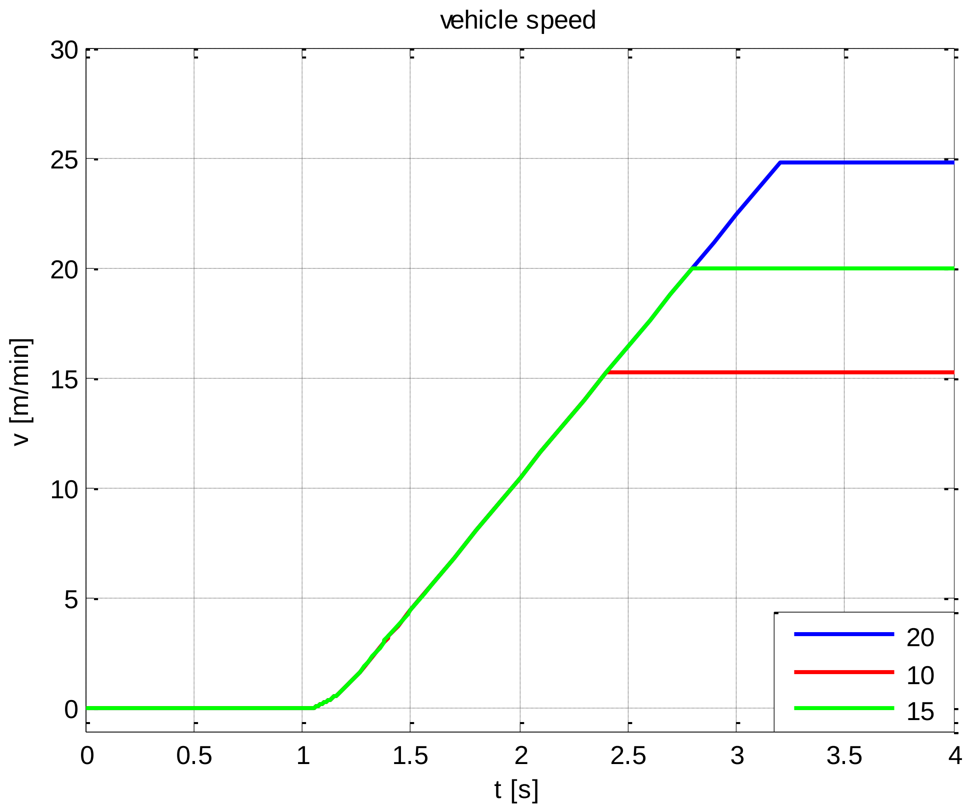


Figure 5.1. *Vehicle speed with nominal speed parameter values of 20, 10 and 15.*

Figure 5.1. shows the simulated operational speeds with different nominal speed parameter values. First, the nominal speed parameter is set to 20, but the operational speed of the device exceeds the desired value. Next, the nominal speed parameter is set to 10 and the simulation run again. As can be seen in figure 5.1, the operational speed with this parameterization would be too low. Finally, the nominal speed parameter value of 15 is selected and the simulation is run again, resulting in the operational speed of 20 m/min. As this information was gained without the need to actually operate the lifting device, it is available before the installation process begins, speeding up the installation.

5.2 Device specific maintenance schedules

The model can be used for planning maintenance schedules. This happens by parameterizing the model with data from the actual device in question and then simulating the device's work cycle. The resulting data can be used to predict the needed maintenance schedule based on the actual work cycle of the device.

The following case simulations compare two situations. In the first one the lifting device is being controlled without the intelligent anti-sway programming, in the second one this feature is switched on. The maintenance significant item being examined is the deflection of a structural beam. The idea is to find differences resulting from different ways of using the device during a similar work cycle.

In the following simulation runs the device performs a predetermined work cycle, in which the hoist first lifts the load, then the vehicle moves for eight meters, after which the beam is moved for two meters. Once the target location has been reached, the hoist lowers the load. This work cycle is depicted in figure 5.2. The first run is performed without the anti-sway function, the second with the anti-sway turned on. This represents two different ways of using the same device with similar work cycles.

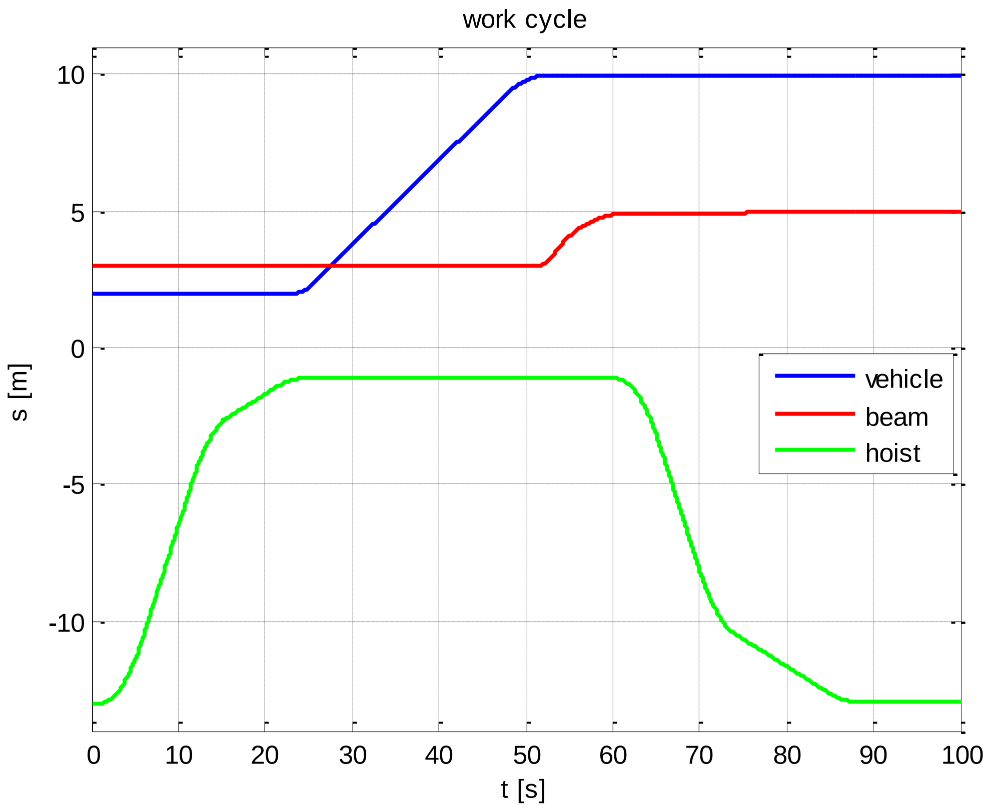


Figure 5.2. *Vehicle movement, beam movement and hoist movement during the work cycle.*

Figure 5.2. shows the work cycle of the device, with the vehicle, the beam and the hoist shown to move as planned. The movement of the vehicle and the pendulum motion of the load swing cause deflections in the structural beam. Figure 5.3. shows these deflections in both cases.

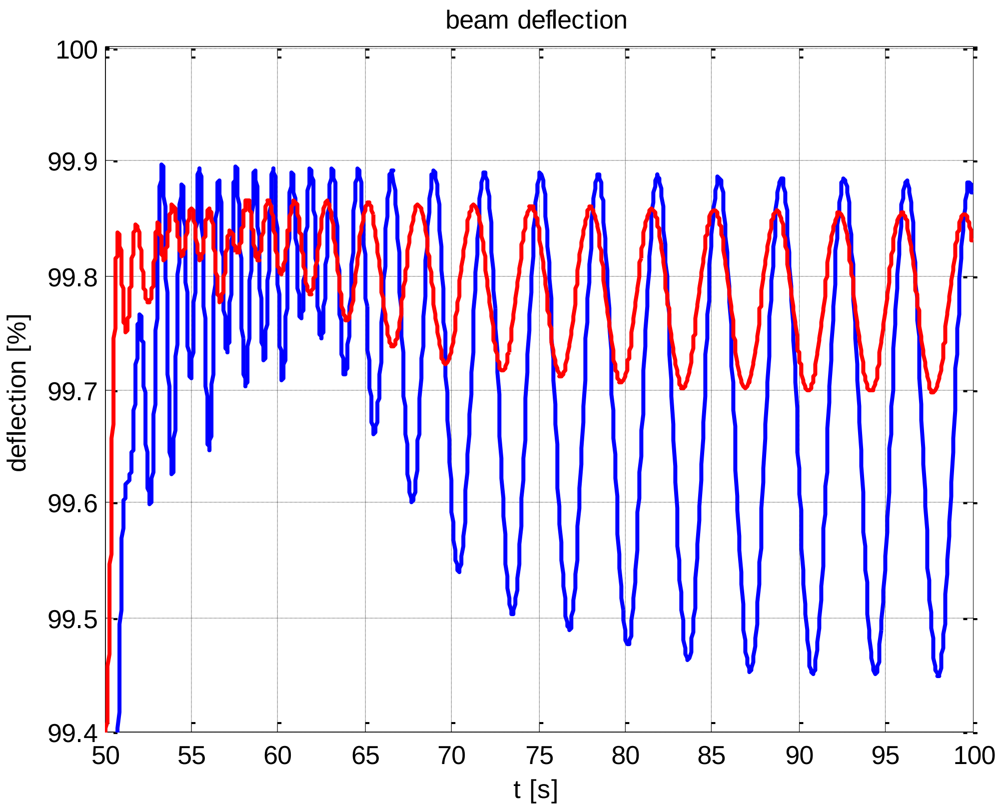


Figure 5.3. *Relative beam deflections, with the anti-sway on case in red and the anti-sway off case in blue.*

Figure 5.3. shows the beam deflection during the work cycle without the anti-sway function and the same with the anti-sway turned on. The picture only shows the events during the last half of the work cycle, when the swinging motion is highest due to the vehicle and the beam movements stopping and their kinetic energies being fully transferred to the pendulum motion. The simulation results show that the automated control reduces the strain on the beam, but more importantly for this case shows the ability to gain maintenance planning information based on the actual use of the device. Enhancing this data with a safe working period calculation would give the two cases individual maintenance schedules.

5.3 Enhancing device usage monitoring with simulation

A usage monitoring application can be used to identify problems in the way the device is being operated. In this scenario the work cycle seen in the previous case is being executed by operating the model manually with a joystick in order to obtain recorded data from manual use. The same work cycle is then executed automatically. The manual operation was first simulated using a fixed step solver ode3 in order to facilitate the real-time run of the model. The joystick commands were recorder and then treated as they would come from an actual device and used to control a variable step simulation. This way the results are comparable with the results of the other cases. Figure 5.4. shows a comparison between the work cycles.

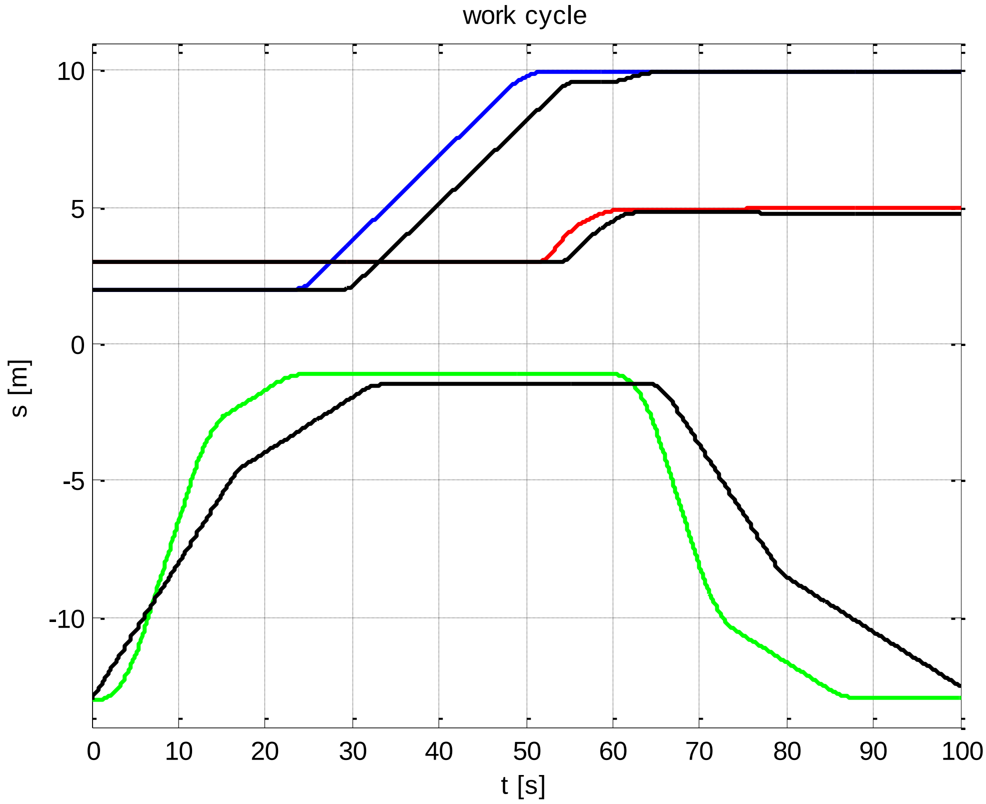


Figure 5.4. *Work cycles during automated and manual operation, with manual operation in black.*

As can be seen in figure 5.4., the manually operated work cycle reaches approximately the same results, but more slowly and less accurately. The data from the two cases can be compared in order to find out their effect on the condition monitoring items of the device. Again, the deflection of the structural beam is investigated and the comparison shown in figure 5.5. Assuming the recorded joystick commands would come from a real device, the effects of manual operation could be compared to an ideal situation.

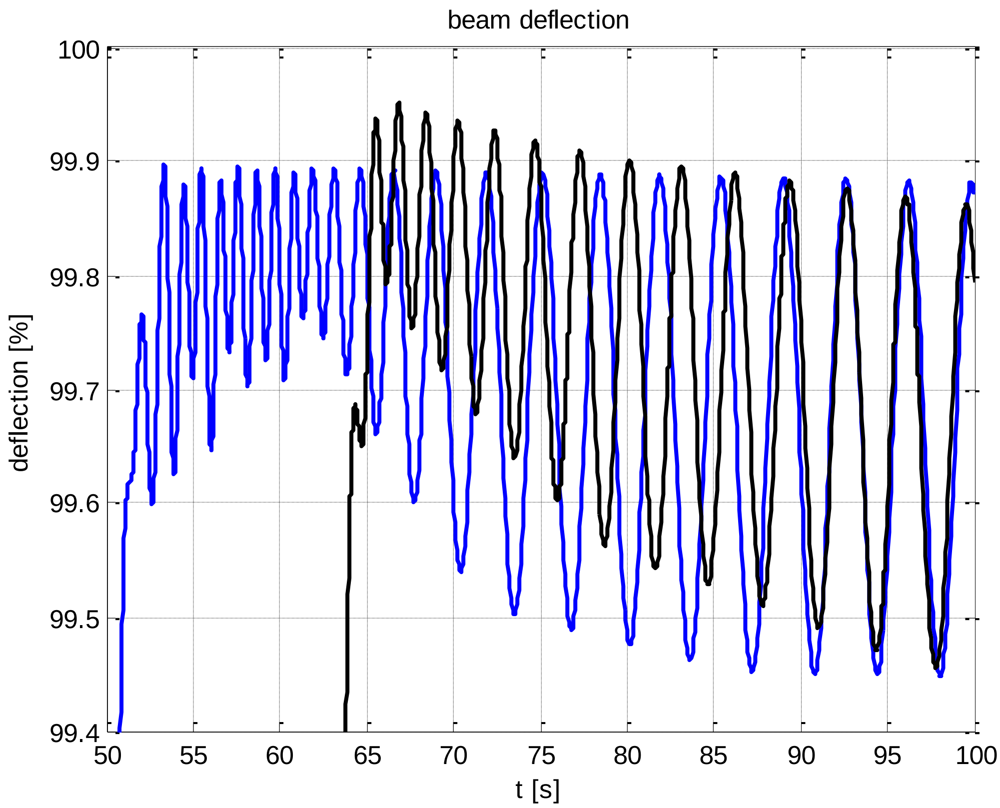


Figure 5.5. *Relative beam deflections during the two cases, with manual drive in black.*

Figure 5.5. shows the differences in the relative deflection of the beam. The effects of the manual operation of the device on the deflection of the beam can now be compared with the deflection values from the ideal run. The results show that during the manually controlled run, the vehicles stop at a later point in time, creating the pendulum motion caused fluctuations later.

5.4 Configuring the device based on simulated work cycle strains

The model can also be viewed as a work-in-progress R&D tool, in which case all of the above mentioned applications would be available already during the product development phase of the product life cycle. The results of these simulations would grow more accurate as the product development phase progresses, but the feedback from simulating the maintenance schedules and use and condition monitoring issues during the product development phase might give valuable insight to the R&D team.

In this case, the maximum torque allowed for the vehicle's driven wheels by the control systems is doubled. This could represent choosing more powerful motors for the vehicle or just finding the maximum torque that can be allowed by the PLC without considerable impacts on the maintenance needs of the device. First, the PLC ramp slopes and nominal speed value are configured using the method described in case 1. Then an assumed work cycle is simulated in order to obtain results on the maintenance significant items, the beam deflection in this case, and the results are compared to those using a smaller maximum torque value. The device work cycle is the one described in figure 5.2., the load is again the heaviest allowed and the desired operational speed for the vehicle is 20 m/min. The torque value is doubled from the previous simulations. Figure 5.6. shows the calibration of the nominal speed value in the case of the larger torque.

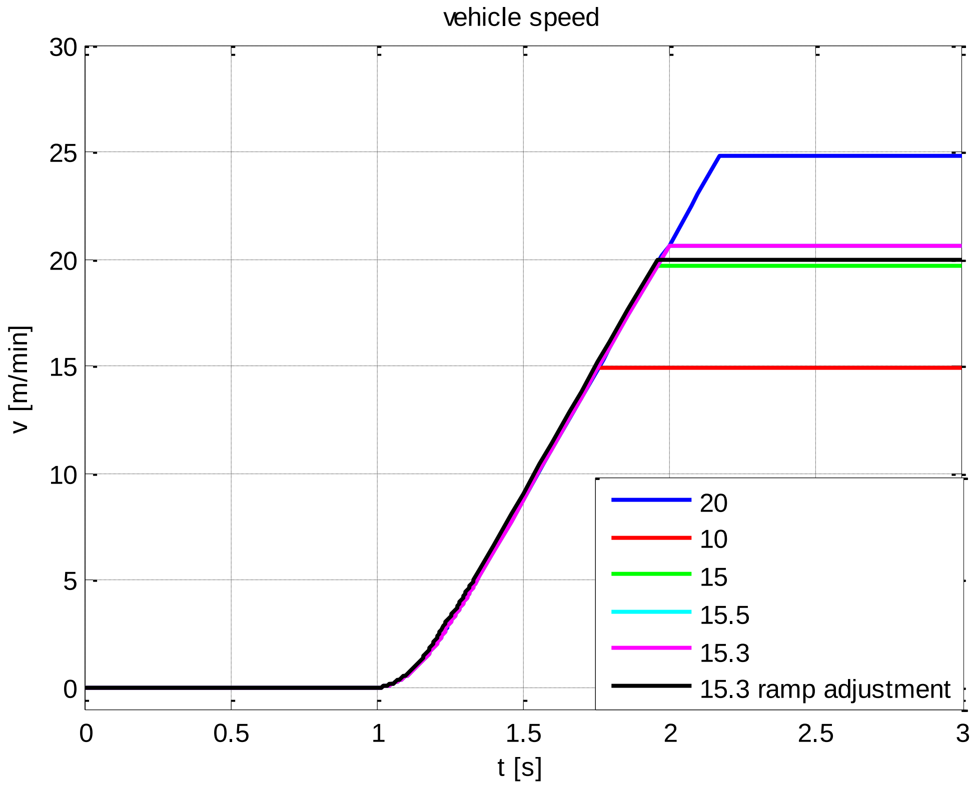


Figure 5.6. *Vehicle speeds with the nominal speed parameter values of 20, 10, 15, 15.5, 15.3 and 15.3 with adjusted acceleration ramps.*

Figure 5.6. shows the different operational speed curves in the situation where the vehicle moves for 20 seconds. The nominal speed parameter value goes through an iteration sequence of 20, 10, 15, 15.5 and 15.3. The last two values give the same operational speed because the nominal speed parameter itself is not the only parameter in the PLC having an effect on the operational speed. The speed is now close enough, so the PLC acceleration ramp slope values are adjusted to reach the desired operational speed. After the PLC has been configured, the work cycle with a twice as high torque value can be simulated and the resulting beam deflections compared. The comparison of the two work cycles is shown in figure 5.7.

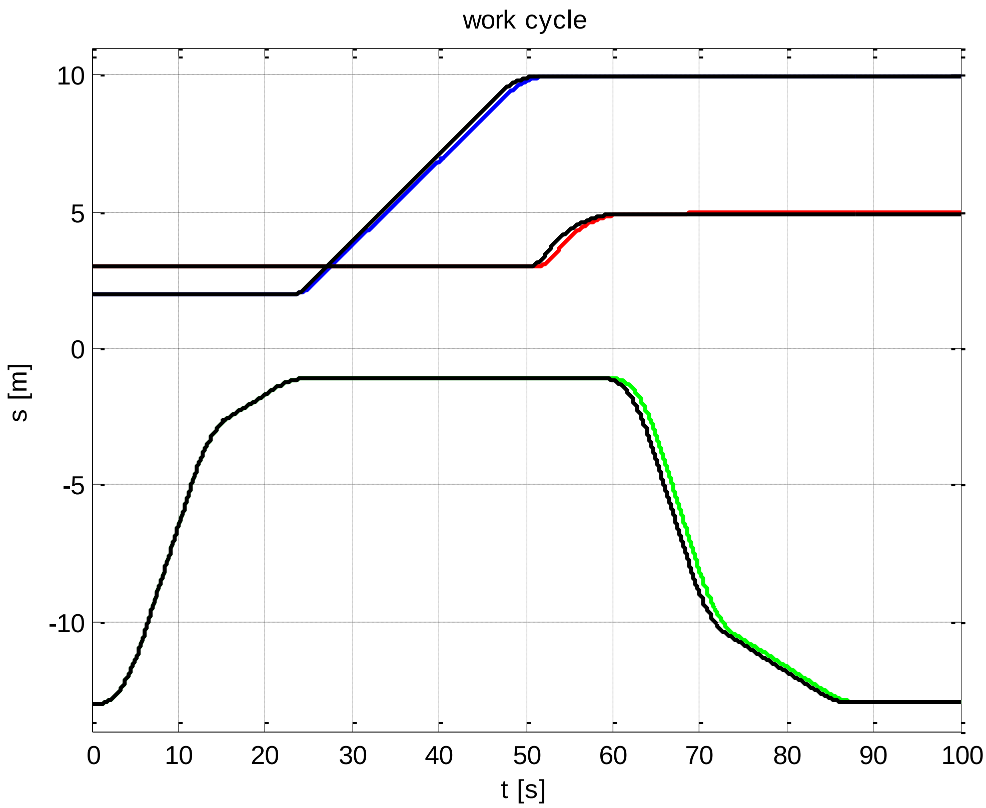


Figure 5.7. *Work cycles in the two cases, the double torque case in black.*

Figure 5.7. shows that the work cycle time with the higher acceleration is only slightly faster. Next the beam deflections caused by the two cases are compared in figure 5.8.

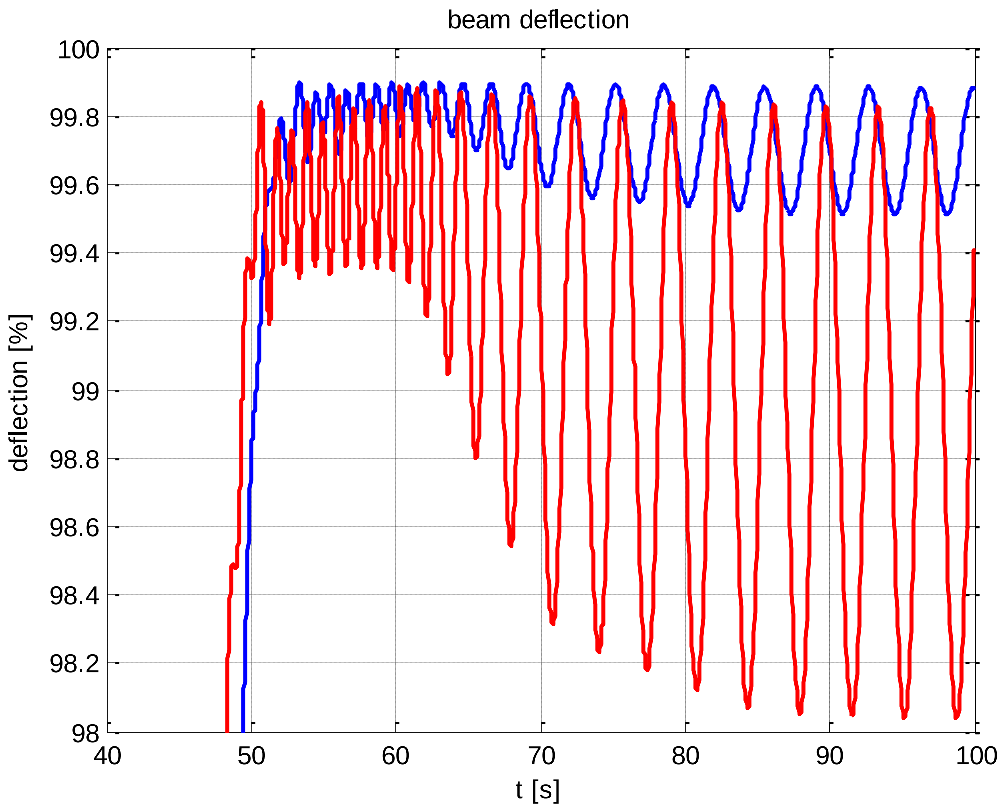


Figure 5.8. *Relative beam deflections in the two cases, with the double torque case in red.*

Figure 5.8. shows the deflections of the beam during the work cycle in the cases of the two torque values. It can be seen that the deflection is smaller with the smaller torque value. This is due to the lower acceleration causing smaller pendulum motions and the smaller wheel slips causing different kind of movement of the vehicle. Repeating the process allows the discovery of the motor torque optimal for the work cycle.

5.5 Marketing simulator

The model can be used as an argumentation tool for marketing. The above comparison results can be used as an argumentation on behalf of the automated functions. The saved location coordinate data can be used to drive visualization tools in order to create marketing videos.

6. DISCUSSION ON SIMULATION UTILIZED IN SMART SERVICES

The model was used to demonstrate simulation as a tool for various smart services, process data into information and gain new data unavailable through physical measurements. Further processing into information and the possible uses for such information are discussed next, as well as possibilities for connecting the model to a larger concept. The idea of simulation is to gain new data or to refine existing data into information. Most applications are created to optimize one aspect or another in the product, its use or some other facet of its life cycle.

The model at this stage does not represent any real device, which rules out the use of actual measurement data for comparisons. The demonstration cases are therefore hypothetical and demonstrate the function of the model, the data available from the simulation runs and its possible uses. There is no reason to doubt the possibility of further developing the model to represent a real device and therefore no reason to doubt that the following examples could not be updated to become actually useful tools. It is also worth noting that this type of a situation does exist within a product's life cycle, in the product development phase. During this phase no actual measurement data is available and as the design is not yet complete, some parts of the model remain generalized.

6.1 Discussion on the cases presented

The installation application provided the needed information, the nominal speed parameter for the PLC. Real world parameter tuning methods could be applied in the planning of the simulation runs. The speed value gained depended on the structure of the device, the load being lifted and the maximum permitted torque. More operating conditions, such as temperature, could be taken into account with suitable modifications to the model. This would then give device specific values to aid the installation process.

The maintenance planning tool simulated a simple work cycle and one maintenance specific item, the beam. Comparable results of the structural strains on the device were gained. The comparison of the strains already gives an idea of which way of operating the device is better suited for the simulated work cycle. The information gained should be further refined by safe life calculations or closer examination with the aid of FEM-models in order to create maintenance schedules for both cases, with and without the anti-sway programming. In reality such safe life calculations are performed based on the number of starts and stops of motors and mass of the load being lifted. As the initial values for these calculations remain the same in both of the cases studied, both situations would give an identical reduction in safe life, which however does not correspond to the actual status of the device.

The usage monitoring tool revealed the manual operation to result in a slightly slower execution of the work cycle and to cause altered strains on the device. The information gained can be formulated into recommendations for the user. The work cycle comparison could by itself be used to recognize either damaging ways of operating the device or problems in the working environment of the device. The information could either indicate bottlenecks in the entire process or a need to change the layout of the device's environment. On the other hand, if bottlenecks have been identified using other methods, the work cycle simulation comparison could be used to pinpoint them by analyzing major differences between the manual and ideal operations. Such differences might also indicate mechanical faults in the device, if no other reason for the aberrations could be found. The strain comparison could be used to indicate major problems with the way the device is being used and then alarm the operator, advising them to correct the way they operate the device in order to reduce major strains to the components. Taking into account psychological and user issues of course; no one wants to be corrected all the time.

The R&D enhancement tool proved to be able to compare the effects of different driving motor torque values on the maintenance significant item (MSI), and the work cycle. This was only the first few cycles of the iteration. Further repetitions of the process would give a more accurate idea on the limits of the torque value and this information could be used in the selection of the driving motor in a case where the intended work cycle of the device is known and maintenance schedule is a key optimization target. The device specific PLC-parameters were also gained during the process.

All of the simulation results presented could be used for argumentation during a sales event or used to identify which qualities of the device the marketing team should emphasize. The beam deflection comparisons demonstrate the effectiveness of the sway-removal programming of the PLC and the work cycle times and the related beam deflection values demonstrate the usefulness of the automated positioning feature, which was used in some of the cases to represent the ideal control situation also. If the customer's work cycle and other parameters are known, the results can be targeted to that customer.

6.2 Further service potentials

The model and the simulation results offer a starting point for many smart services tools. The cases presented can be further enhanced by increasing the level of automation in the simulation and further refining the information gained with other models or calculation tools. The information gained can be used in larger contexts and refined into knowledge.

6.2.1 Installation parameterization application

An even more efficient tool would be created by enabling the model to parameterize itself and find the correct speed values automatically. This self-parameterizing installation tool could, using optimization routines, be created so that the installation personnel would only need to insert certain values based on the device's intended use, such as accelerations, speeds, load masses and work cycle data. The program would then find the optimal parameters automatically and output the required PLC parameters. This type of tool would enhance the installation service offered by the manufacturer.

Saved to an active database, these parameter values could also be analyzed. They could be compared to the final real world values, saved to the database by the installation crews, to determine how accurate results the installation tool gives and to identify possible needs for updating it.

6.2.2 Maintenance planning application

If the simulation is repeated from time to time based on parameters gained from measurements made during the device's operation and its actual work cycle, the maintenance schedule can be adjusted accordingly. Or, if the maintenance schedule cannot be altered, for example because a factory cannot be taken off line at will, the work cycle of the device can possibly be adjusted to allow for longer component safe lifes. Several different MSIs can be taken into account through simulation and using optimization routines, an even more accurate and effective maintenance schedule can be created, allowing for the maximum number of MSIs to be serviced during any given maintenance stop, thereby minimizing the number of maintenance stops during a device's life cycle.

If this kind of maintenance need information is available from all the devices along a production line, it can be compared to the needs of the production itself to adjust both the devices' work cycles and the entire production to create the optimal balance between machine maintenance and factory output. This optimization could also be done automatically using a suitable simulation program that works in conjunction with a model of the production line as well as with models of individual machines. The results presented above are therefore only the beginning of larger iteration cycle for optimizing an entire production line's operation. If simulation models would produce universally compatible output data, the manufacturer of the device could provide the model to the owner of the device.

These different ways of using the device and their effects on the maintenance cycles should be made available to the R&D department through active database architecture for more accurate development decisions. Analyzing the maintenance schedules of an entire fleet of devices and identifying trends could be used to indicate product development needs.

6.2.3 Usage monitoring application

The comparison of the beam deflection during the manual operation work cycle and the ideal work cycle reveals deviations. It would be possible to place threshold values for such maintenance items and inform the user if these values are exceeded. Creating these values with simulation based on the actual situation of the device means they are more accurate. This sort of enhanced use analysis could either be offered as a service or the tool could be sold to the customer.

A condition monitoring application could compare the ideal case results data with actual measurement data to identify changes in the device's behavior. When certain operational limits are exceeded, a component level comparison between the measurement data and simulation data could be performed in order to discover the origin of the discrepancy. Or if there isn't enough measurement data available, the simulation results could be used to discover which components could possibly be the source of error.

Analyzing user behavior through simulation could be used to find faulty components in the device by identifying corrective patterns in the operator's actions. If a component in the machine does not work optimally, the user will instinctively operate the machine in a distinct way to compensate for the fault. User data comparisons enhanced by simulation could be used to pinpoint the component causing the anomalies in the user behavior. This could complement other ways of detecting faults, or be used in a situation where other measurement data is unavailable. The simulated strain data could also be used as a basis for constantly updated device specific maintenance schedule.

6.2.4 Product development application

The simulations could happen automatically. A carefully planned iterative design tool could find optimal configurations for the entire machine construction based on conditions of a customer's process. If the product design would be modular, the optimal configuration of the device, based on the optimization criteria, could be created automatically. This would also require submodels and parameters to be semantically tagged and machine readable. The optimization criteria demonstrated included work cycle execution time and the maintenance schedule, but other factors could also be taken into account. With the information gained, a motor for the device can be chosen, but then the iteration should continue with other variables such as energy consumption, heat and expenses added to the iterated items.

The accuracy of the data must also be monitored. In this model, for example, the electric motors are modeled in a very straightforward manner, acting to provide only the torque value to the wheel models. The motor torque needs could be iterated, but issues related to energy consumption and heat for example could not. More accurate motor models can be added in the further phases of the iteration cycles in order to gain more accurate information.

6.2.5 Possible uses for the model in marketing

The simulation results can also be used in the creation of a marketing tool using a video game physics engine. These engines require parameters of their own, which are not necessarily based on real physics and therefore cannot be obtained from data sheets or other documentation. Comparison data from a simulation model would make it considerably quicker and easier to create the needed values for a marketing simulator, as all the needed data could be gained quickly and without the need for measurements. It could also be possible to create a marketing simulator automatically based on pre-programmed modular game world objects and parameters gained from the customer. A simulator game based on a simulation model would also enable the marketing of a product that does not physically exist yet.

If such a marketing simulator is used, recording data from how the customers use it and analyzing the data could give ideas on what the customers want, what they prefer, what sort of qualities they are looking for before making the decision of purchase. This information could be used in the planning of the marketing strategies and tactics. The information might also be useful in product development. If a customer’s work cycle data is available beforehand or even during the sales event, the simulation model could be parameterized to correspond to that data and all of the results above could be used for argumentation.

7. CONCLUSIONS

The research revealed several ways of using simulation to enhance the services related to a product along its entire life cycle. Many of these would greatly benefit the industrial service business mindset. The research also discovered common problems related to the use of simulation. These could be summed as lack of compatibility, lack of coordination and lack of planning. The software industry's lack of standardization creates difficulties in utilizing simulation to its fullest extent from the point of view of a manufacturing company.

The process of modeling the lifting device in this thesis turned out to exemplify some of these problems. The lack of a clear objective and the subsequent changes of the objective cost time and resulted in modeling decisions which later hindered the achievement of the latest objective set. No survey of other models based on the lifting device in question was made, though it can be assumed that there are such models. While the model built demonstrates several uses for simulation, some of its submodels would require more detailed functions to be useful in real world applications.

These real world problems prove firsthand the need of planning. It is not enough to plan the model building itself, the use of simulation should be seen as companywide asset in order to avoid the same work being done over and over again and to gain full use of the models and data already available and to make the models and the simulation results available for anyone who might need them. Another problem encountered was the calculation power required to model certain physical phenomenon. The advances of computer technology make this problem a very temporal one. Even so, at the moment it must be taken into account. Based on the application and the required simulation data, some parts of the models may need to be simplified, even heavily.

The model building should be planned with a clear view of the objectives, with knowledge of all the tools available and access to all the information and data available. Good modeling conventions, such as testing the proper functioning of one subsystem at a time before adding them to the top level model should be followed. If calculation power issues arise, simplifications should be made only with a full knowledge of their effects on the simulation results and all the applications linked to the model. When the model is in use, it should be acknowledged that the model processes data into information and can sometimes attach preconceptions to that information, affecting the way the users interpret it. There are two different scenarios of model building for the purposes of smart services: building a model for a new product alongside its design process and building a model of an existing product. Both have their specific needs and considerations.

Simulation models are a very effective tool for service business, among other things. On the other hand, it is difficult and resource consuming to build a model. One model could be used for many purposes, if designed so from the start. Therefore it can be concluded that to effectively utilize simulation to support its products and services, a company should see simulation models as multi-purpose tools that follow a product for the entirety of its life cycle. Modeling should be a part of the product life cycle process and be seen from a systems engineering point of view.

The identified needs of the utilization of simulation are a data-architecture and effective and accurate models. Model building begins in the product development phase. These models should be designed to have multiple uses and it should be possible to adapt them for new ones. The required simulation models of a product should be built as a part of its design process, used as tools in the design process and then be passed on to be used as tools in every step of the product's life cycle. The models should be designed so that they are suitable for multiple uses, are compatible with each other and are compatible with models from other manufacturers. The models can then follow the product during its life, acting as tools for different purposes.

There is a need for standards to ensure that models from different machine manufacturers interact properly and can be used to simulate an entire plant. Several different machines in one factory mean several different models from different manufacturers; these models should be able to interact. If these demands would be met and problems solved, a manufacturing company would be able to sell or offer its models to the customer.

With the advent of such things as cloud computing and industrial internet, the amount of data created by industrial systems and the availability of calculation power mean that every manufacturer has to deal with entirely new digital requirements and challenges. Coupled with industrial service thinking and seeing products as platforms of service delivery, this new industrial revolution opens up many possibilities. Service providing manufacturers become merchants of information by practical necessity. How they gather, create and process this information is a challenge requiring paradigm shifts and new ways of thinking. There is no way to avoid this, only different ways of embracing it. The use of simulation to turn data into information is a part of this development of industry. It is an important part, but only a part. The way it differs from other ways of data refinement is the fact that it is rather independent of the physical world and manufacturers can develop their simulation environments without costly upgrades of the physical processes, making it an easy first step on the way of making the best out of the flood of information heading their way in the near future. Finally, it should be remembered that simulation is never the truth; you cannot drill oil from a map, but a map is a useful tool nonetheless.

Future research topics in this area could include seeing simulation as a part of the entire product life cycle, not just individual applications or solutions to singular problems. The handling of product-related data is presently shattered over a large amount of formats, programs and conventions. It would be useful to discover ways and methodologies to create product related data in such ways as to make it easy to use over the entire product life cycle. That means continued research in the field of semantic data. Also needed are methodologies to spread these new conventions effectively inside companies.

SOURCES

Ahvenniemi, O. 2012. Recognizing the opportunities for new service-enhanced products. Master of Science Thesis. Tampere. Tampere University of Technology. 78 p. + appendices 1 p.

Al-Hussein M., Niaz, M., Yu, H., Kim, H. 2006. Integrating 3D visualization and simulation for tower crane operations on construction sites. Automation in Construction 15, 5, pp. 554 – 562.

Argusa R., Mazza G., Penso R. 2009. Advanced 3D Visualization for Manufacturing and Facility Controls. 2nd Conference on Human System Interactions, 2009. HIS ‘09. 21-23 May 2009, Catania, Italy. pp. 456-462.

Boström, H., Andler, S., Brohede, M., Johansson, R., Karlsson, A., van Laere, J., Niklasson, L., Nilsson, M., Persson, A., Ziemke, T. 2007. On the Definition of Information Fusion as a Field of Research. Skövde. IKI Technical Reports; HS- IKI -TR-07-006. 8 p.

Brunsmann, J., Wilkes, W., Brocks, H. 2011. Exploiting Product and Service Lifecycle Data. Proceedings, PLM11 8th International Conference on Product Lifecycle Management, Eindhoven, The Netherlands, 11-13 July, 2011. IFIP Working Group 5.1. pp. 309-318.

Benn, L., Burton, B., Ireland, J., Wang S., Harley, R. 2004. Model Gantry Crane with Dynamic Feedback Swing Control. Proceedings, 2004 IEEE International Symposium on Industrial Electronics, 4-7 May 2004, Ajaccio, France. pp. 265-271.

De Vin, L., Ng, A., Oscarsson, J., Andler, S. 2005. Information fusion for simulation based decision support in manufacturing. Robotics and Computer-Integrated Manufacturing Volume 22, Issues 5–6. pp. 429–436.

FIMECC FutIS. 2014. Future Industrial Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.fimecc.com/content/futis-future-industrial-services

Fritzson, P. 2011. Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica. Singapore. John Wiley & Sons Inc. 211 p.

Fukushige, S., Yamamoto, K., Umeda, Y. 2012. Lifecycle scenario design for product end-of-life strategy. Journal of Remanufacturing 2012 [Electronic journal]. 2:1, 15 p [Accessed 17.12.2013]. Available at http://www.journalofremanufacturing.com/content/2/1/1

García Pájaro, H. 2012. A 3D-Real Time Monitoring System for a Production Line. Master of Science Thesis. Tampere. Tampere University of Technology. 62 p. + appendices 14 p.

Ghafari, S. 2010. A Model Based Condition Monitoring System for Rotary Machinery. Lecture slides. 3rd international CANDU In-Service-Inspection and NDT in Canada 2010 conference. June 14-17 2010, Toronto, Canada [Electronic document]. [Accessed 15.6.2013] Available at http://www.ndt.net/article/ndt-canada2010/papers/Ghafari.pdf

Hesselbach, J., Westernhagen, K. 1999. Disassembly simulation for an effective recycling of electrical scrap. Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. First International Symposium On EcoDesign '99. 1-3 February 1999, Tokyo. pp. 582 – 585.

Hiab. 2014. Hiab Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.cargotec.com/en-global/hiab/services/Pages/default.aspx

Huovinen, M. 2010. Large Scale Monitoring Applications in Process Industry. Dissertation. Tampere. Tampere University of Technology. Publication – Tampere University of Technology. Publication 867. 119 p.

ISO 13372:2004. 2004. Condition monitoring and diagnostics of machines - Vocabulary.

John Deere, 2010. Forestry Machine Simulators. Brochure. Deere & Company. Finland. Offset Ulonen 4-2010. 8 p.

Kalmar. 2014. Kalmar Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.cargotec.com/en-global/kalmar/services/Pages/default.aspx

KITARA. 2010. Research Programme on the Application of Information Technology in Mechanical, Civil and Automation Engineering, KITARA (2005–2009). Publication of the Academy of Finland 1/10. 55 p.

KONE. 2014. KONE Services. [WWW]. [Accessed 26.1.2014]. Available at: https://www.kone.com/en/solutions/services/

Konecranes. 2014. Konecranes Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.konecranes.com/service

Lakka, S. 2013. Development of simulation and control system for bridge crane assisted automated warehouse. Master of Science Thesis. Lappeenranta. Lappeenranta University of Technology. 97 p. + appendices 1 p.

Lalonde, B.J., Zinszer, P.H. 1976. Customer service: Meaning and measurement. National Council of Physical Distribution Management.

Law, A., McComas, M. 2000. Simulation-based Optimization. Proceedings of the 2000 Winter Simulation Conference, 10-13 Dec 2000, Orlando, Florida. pp. 46-49.

LMS Imagine.Lab AMESim. 2012. LMS Imagine Lab AMESim Rev 11 SL1 ver 11.1.0 Help file.

Lumme, V. 2012. Intelligent Interpretation of Machine Condition Data. Tampere. Tampere University of Technology. Publication – Tampere University of Technology. Publication 1096. 104 p.

Lupton, R. 2009. Measuring tidal variations in ‘g’ using Trinity’s pendulum clock. Fourth-year undergraduate project. Trinity College, Cambridge. [Electronic document] 50 p. [Accessed 13.6.2013] Available at http://www.trin.cam.ac.uk

MacGregor. 2014. MacGregor Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.cargotec.com/en-global/macgregor/services/Pages/default.aspx

Metso Mining. 2014. Metso Mining and Construction Services. [WWW]. [Accessed 26.1.2014]. Available at:
http://www.metso.com/miningandconstruction/mct_service.nsf/WebWID/WTB-100323-22576-818C1?OpenDocument#.U0wXJEDecnI

Metviro 2009. Virtual and intelligent learing environment for forestry machine mechanic -project. [WWW]. North Karelia College, Tampere University of Technology. Updated 24.3.2009. [Accessed 12.2.2014] Available at: http://matriisi.ee.tut.fi/metviro

Ming, Q. 1997. Sliding Mode Controller Design for ABS System. Master of Science Thesis. Blacksburg, Virginia. Virginia Polytechnic Institute and State University. [Electronic document] 83 p. + appendices 5 p. [Accessed 28.5.2013] Available at http://scholar.lib.vt.edu

Nurmi, J. 2013. Data-driven virtual views to support mechatronics machine design process. Tampere. Tampere University of Technology. 73 p. + appendices 13 p.

Nykänen, O., Koskinen, K., Ranta, P., Salonen, J., Aaltonen, J., Nurmi, J., Helminen, M., Alarotu, V., Salomaa T., Pohjolainen, S. 2013. Virtuaalinen konelaboratorio ja semanttinen mallinnus konejärjestelmän suunnittelun tukena, Loppuraportti, Semogen II –hanke. Tampere. Tampere University of Technology. Smart Simulators research group. 46 p. + appendices 4 p.

Outotec. 2014. Outotec Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.outotec.com/en/Products--services/Services/

Paajanen, R., Kuosmanen, P. 2010. White Paper: Finland and Data Reserves. TIVIT (ICT SHOK) p. 15. [Electronic document] [Accessed 6.11.2013] Available at www.tivit.fi

Paloheimo, K., Miettinen, I., Brax, S. 2004. Customer Oriented Industrial Services. Espoo, Helsinki University of Technology, BIT Research Centre. 91 p. + appendices 4 p.

Robinson, S. 2004. Simulation: The Practice of Model Development and Use. Great Britain. John Wiley & Sons Ltd. 336 p.

RobotStudio Plastics Sales Tool. 2006. PDF brochure. ABB, Västerås, Sweden. May 2006. p. 2. [Accessed 13.4.2014] Available at: http://www05.abb.com/global/scot/scot241.nsf/veritydisplay/f22efee4fcb324d0c12571d8002688a5/$file/rs-pst%20datasheet%20print.pdf

Rodriguez Alvarado, J. 2010. Distributed Simulation in Manufacturing using High Level Architecture. Master of Science Thesis. Tampere. Tampere University of Technology. 77 p. + appendices 3 p.

Ruukki. 2014. Ruukki Services. [WWW]. [Accessed 26.1.2014]. Available at: http://www.ruukki.com/Products-and-solutions/Steel-services-and-support

Salmi, T., Pajunen, S. 2010. Lujuusoppi. Tampere, Pressus Oy. 462 p.

Salonen, J., Nykänen, O., Ranta, P., Nurmi, J., Helminen, M., Rokala, M., Palonen, T., Alarotu, V., Koskinen, K., Pohjolainen S. 2011. An Implementation of a Semantic, Web-Based Virtual Machine Laboratory Prototyping Environment. The Semantic Web – ISWC 2011, Lecture Notes in Computer Science, 2011, Vol. 7032/2011, pp. 221-236.

Sato, Y., Hashima, M., Senta, Y. 2007. Virtual Product Simulator (VPS). Fujitsu Scientific & Technical Journal, 43, 4, pp. 475-485.

Smith, T., Diez Oliván, A., Barrena, N., Azpiazu, J., Agirre Ibarbia, J. 2011. Remote Maintenance Support in the Railway Industry. Joint VR Conference of euroVR and EGVE, 2011. 20-21st September, 2011, Nottingham, UK. VTT Technical Research Centre of Finland. pp. 40-46.

Stark, J. 2011. Product Lifecycle Management: 21st Century Paradigm for Product Realisation. Springer. 561 p.

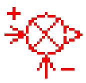
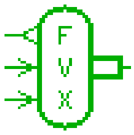
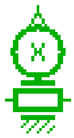
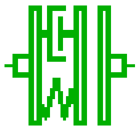
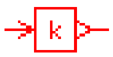
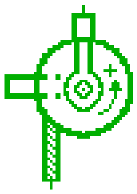
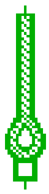
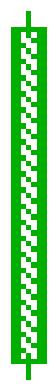
Systems Engineering Fundamentals. 2001. Fort Belvoir, Virginia. Defense Acquisition University Press. 216 p.

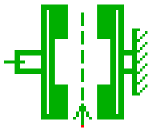
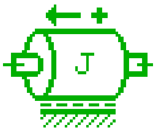
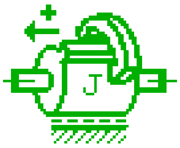
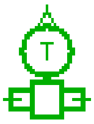
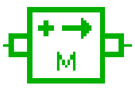
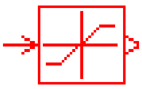
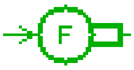
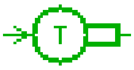
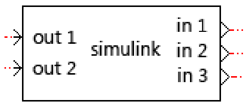
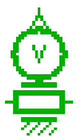
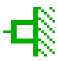
Tamberg, S. 2011. Design and Implementation of a Traction Control System and Electrical Differential to Hybrid Industrial Vehicle Environment. Master of Science Thesis. Lappeenranta. Lappeenranta University of Technology. 103 p.

Vainio, V. 2012. Comparative research of PLM usage and architecture. Master of Science Thesis. Tampere. Tampere University of Technology. 73 p.

APPENDIX: AMESIM SUBMODEL BLOCKS

Table A.1. *The AMESim submodels used in this thesis with their graphical block presentations and short descriptions of their operation (LMS Imagine.Lab AMESim 2012).*

	**Comparison junction differencing inputs (JUN3M)** Subtraction junction. Outputs the difference between the input signals.
	**Conversion between linear mechanical and signal (FVXSG1)** Conversion between linear force, velocity, and displacement variables and signal variables.
	**Displacement sensor (DT000)** Displacement transducer. Outputs a displacement value as a signal with null units.
	**Elastic contact with no states (LSTP00A)** Elastic contact between two bodies capable of linear motion. Contact force consists of a spring force and a damping force.
	**Gain (GA00)** Multiplication of the input signal by a user specified gain.
	**Ideal winch (WINCH01)** Two dimensional motion of an ideal winch. Displacement and velocity of the rotation and translation of the winch are included. A rope model can be attached.
	**Rope end (REND001)** Interface to connect standard AMESim submodels and rope models, transfers velocity and force information.
	**Rope with stiffness and viscous friction (ROP0001)** Rope model taking the stiffness of the rope and its viscous friction into account by using an effective value depending on the rope length.

	**Rotary Coulomb and stiction friction represented by a reset integrator model (FR1R0010)** Friction torque generator. The friction torque is modeled as stiction and Coulomb friction.
	**Rotary link (TILI0C)** Link between rotary submodels. The velocity at the output port is passed without modification to other ports. The torque output is equal to the sum of the torques at the two input ports.
	**Rotary load with friction (RL04)** Rotary load acted on by two external torques. Includes viscous friction, Coulomb friction and stiction.
	**Rotary load with friction and configurable endstops (RL24)** Rotary load acted on by two external torques. Includes viscous friction, Coulomb friction and stiction. The angular displacement is limited to a specified range.
	**Torque sensor (TT000)** Torque transducer. Outputs a torque value as a signal with null units.
	**Two-port mass model (MAS002)** One-dimensional motion of a two ports mass acted on by two external forces.
	**Saturation element (SAT0)** Limiting the output signal between a minimum permitted level and a maximum permitted level.
	**Signal-to-force conversion (FORC)** Conversion of a dimensionless signal input to a force with the same value in Newtons.
	**Signal-to-torque conversion (TORQC)** Conversion of a dimensionless signal input to a torque with the same value in Newton metres.
	**Simulink interface icon** Passes input signals to Simulink and outputs signals from Simulink.
	**Velocity sensor (VT000)** Velocity transducer. Outputs a velocity value as a signal with null units.
	**Zero speed source (V001)** Zero velocity. Constant displacement and acceleration.