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Benefits of digitalized asset management for steam turbines

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Abstract of master's thesis

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Abstract

Steam turbines are considered long-lived and require little attention during normal operation. Cost optimizations due to infrequent demand for turbine expertise, together with retiring workforce, have resulted in increasing shortage of know-how. Digitalization could substitute unavailable turbine resources, but the projects and investment have been challenging to initiate and incentivize.

The objective of this thesis was to map the benefits of digitalized steam turbine asset management, what kind of challenges digitalization could mitigate and how the implementation could be facilitated. The research confirmed that turbine operating companies lack the domain know-how and resources required for some current systems and demands. Prolonging of overhauls and deficiencies in asset management, such as insufficient documenting and data utilization, were observed to be other main challenges. Increased downtime and unoptimized practices and systems reduce efficiency, usability, reliability and availability.

Advanced diagnostics in condition monitoring systems could increase availability and reliability by enabling optimized condition-based maintenance and facilitate shorter overhauls by reducing unforeseen findings. Solutions and service that allow faster fact-finding in anomalies would increase availability as well. Asset management systems with more connectivity, centralization, user-friendliness and AI would reduce downtime by enhancing planning, documenting and spare part management. Such systems could also increase usability and the overall efficiency of operations and maintenance.

Main hindrances for digitalization are the imbalance between costs and perceived added value, and insufficient focus on the usability of asset management systems. Development of advanced solutions in current business models is disincentivized. Long-term contracts could enable the implementation of best practices, reduce risks and incentivize higher quality of services. Partnership business models facilitate mutual benefits better than short-term and stand-alone services.

Keywords digitalization, asset management, steam turbines, remote diagnostics, condition monitoring, maintenance

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Tiivistelmä

Höyryturbiinit ovat yleensä pitkäikäisiä ja vaativat vain vähän huomiota normaalin käynnin aikana. Huollon ja turbiiniosaamisen harvan tarpeen takia höyryturbiinien käyttö- ja hallintakustannuksista on jatkuvasti säästetty. Tämä, yhdessä eläköityvän työvoiman kanssa, on johtanut krooniseen tietotaidon puutteeseen höyryturbiinilaitoksilla. Digitalisaatiolla voisi korvata puuttuvia resursseja, mutta projektien ja investointien kanssa on ollut ongelmia.

Tämän diplomityön tarkoituksena oli kartoittaa höyryturbiinien digitaalisen käyttöomaisuuden hallinnan hyötyjä, millaisiin haasteisiin se voisi vastata, ja mitä digitalisaation hyötyjen menestyksekäs implementointi vaatisi. Tutkimus varmisti, että loppukäyttäjillä on puutetta turbiiniosaamisesta ja -resursseista, joita tämänhetkiset systeemit ja tarpeet vaatisivat. Muita suuria haasteita olivat huoltojen pitkittymiset ja puutteet käyttöomaisuuden hallinnassa, kuten riittämätön dokumentointi ja mitatun datan hyödyntäminen. Pitkittyvät huollot ja optimoimattomat toiminnot kasvattavat epäkäytettävyysaikaa ja pienentävät tehokkuutta, käytön helppoutta ja luotettavuutta.

Kehittyneen turbiinidiagnostiikan hyödyntäminen kunnonvalvonnassa voisi kasvattaa käytettävyyttä ja luotettavuutta mahdollistamalla turbiinin todelliseen huoltotarpeeseen perustuvan huollon. Ennakoivalla analytiikalla voitaisiin vähentää odottamattomia löydöksiä, jotka ovat yksi yleisin syy huoltojen pitkittymiseen. Käytettävyyttä lisäisivät myös ratkaisut ja palvelut, joilla nopeutettaisiin ongelmanratkaisua häiriötilanteissa. Käyttö- ja kunnossapitojärjestelmien parempi liitettävyys, keskitettävyys ja käyttäjäystävällisyys sekä tekoälyn hyödyntäminen tehostaisivat käyttöomaisuuden, kuten varaosien, hallintaa ja helpottaisivat suunnittelua ja dokumentointia.

Merkittävimpiä esteitä turbiinien käyttöomaisuuden hallinnan digitalisaatiolle ovat kustannusten ja hahmotetun lisäarvon epätasapaino sekä riittämätön huomio käyttöomaisuuden hallinnan optimointiin. Edistyksellisten digitaalisten ratkaisujen kehittämiselle ja loppuasiakkaalle tarjoamiseen ei ole riittävästi kannustimia. Pitkäaikaiset ylläpitosopimukset voisivat mahdollistaa parhaiden käytäntöjen implementoinnin, vähentää liiketoimien riskiä ja tehdä korkeimmankin laadun palveluista ja ratkaisuista kannattavampia. Pitkäaikaiseen kumppanuuteen perustuvat liiketoimintamallit fasilitoivat osapuolten yhteisiä etuja paremmin, kuin lyhytaikaiset erillissopimukset yksittäisille ratkaisuille ja palveluille.

Avainsanat digitalisaatio, käyttöomaisuuden hallinta, höyryturbiinit, etädiagnostiikka, kunnonvalvonta, huolto

Foreword

This Master's thesis was carried out for Siemens Osakeyhtiö between November 2018 and June 2019 as an interview research to better understand the customer needs. Discussion with multiple professionals, whose total energy technology and management expertise can be calculated in the hundreds of years, gave this research all the insight it has. I am very thankful for their input and have tried to present their knowledge to the best of my abilities.

I want to thank my thesis supervisor professor Martti Larmi for the efficient cooperation. My gratitude also goes to my thesis advisor Jussi Uddfolk and all the other ever so encouraging and helpful colleagues at Siemens. The contribution to my occupational development and the confidence that has been placed in me are highly appreciated.

I sincerely thank my parents for all the support along my educational journey, and other family and relatives for being the fabric of my happiness. I am especially grateful for my grandparents for showing me the importance of education and learning. Finally, I thank my friends whose unconditional love and peer pressure have made me a better person.

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Lauri Kare

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Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
AR	Augmented Reality
CBR	Case-Based Reasoning
CCPP	Combined Cycle Power Plant
CHP	Combined Heat and Power
DCS	Distributed Control System
DL	Deep Learning
DNN	Deep Neural Network
ERP	Enterprise Resource Planning
ESV	Emergency Shutdown Valve
IaaS	Infrastructure as a Service
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol
IST	Industrial Steam Turbine
KPI	Key Performance Indicator
M2M	Machine-to-Machine
MaO	Major Overhaul
MiO	Minor Overhaul
ML	Machine Learning
NDT	Non-Destructive Testing
NLP	Natural Language Processing
O&M	Operations & Maintenance
OEM	Original Equipment Manufacturer
PaaS	Platform as a Service
P&ID	Piping and Instrumentation Diagram
PoC	Proof of Concept
RoI	Return on Investment
RPM	Revolutions Per Minute
SaaS	Software as a Service
TCS	Turbine Control System
T&M	Time and Materials
VPN	Virtual Private Network
VR	Virtual Reality

1 Introduction

1.1 Research background

Digitalization is bringing about substantial cost savings, increased efficiency and flexibility across different industries and transforming business models. Digital solutions, such as remote diagnostic services and machine learning, enabled by free-flowing data between smart connected things are anticipated to help coping with diminishing resources. However, while sensor and networking technologies have improved and cheapened simultaneously, and data has proved its worth as a valuable resource, the reality especially in energy and process industry is that plants are still very siloed systems. Data is used predominantly for automation and real-time anomaly detection purposes. Novel digital asset management solutions that require more open use and sharing of data are still implemented with caution and the costs are not considered to be in balance with the benefits.

Steam turbines are expensive and delicate systems operating in extreme conditions, so the sensor and automated maintenance capabilities are limited. Furthermore, most of the research covering the digitalization of turbines, i.e. remote monitoring and diagnostics, optimization and digitalized maintenance solutions, focuses on gas turbines and Combined Cycle Power Plants (CCPP). These systems have different setups, face different challenges and serve different use cases compared to steam turbine plants, and hence also their value chain and digitalization opportunities differ.

Steam turbines can be divided into utility and industrial units. Typical Industrial Steam Turbines (IST) operate in a much more fluctuating environment than utility turbines due to varying processes they are used for. The optimization is not based solely on the power generation requirements, but on the process heat demand such as in pulp and paper industry. They are also generally smaller in terms of capacity and consequently exposed to lower temperatures and pressure levels than their utility and gas counterparts. IST operating companies also have less turbine know-how than utility users and thus their service need differ.

The implementation of digitalized asset management for steam turbines is falling behind gas and wind turbine types and this seems to be partly due to lack of clear business cases to incentivize digitalization efforts and investments. On the other hand, even with clear benefits, digitalization projects have been challenging to initiate. This thesis is trying to clarify the situation and form a better understanding of how to facilitate digital asset management solutions so that the industry remains competitive.

1.2 Research scope and objectives

The objective of this thesis is to map the benefits of digitalized asset management for steam turbines. This is done by first detailing problems, challenges and needs in steam turbine asset management that the experts in related subfields have identified both recently and throughout the years of plant operation. Following, the thesis examines how digitalized asset management solutions could solve these problems, and what other possibilities could come with them. Next the thesis examines what hindrances the implementation of these digitalized solutions faces and how to mitigate them. The result is a review of benefits that digitalized asset management could obtain for steam turbines in the near future.

The scope of the research is limited to steam turbine systems and excludes other equally important components of steam and heat production and power generation, such as generators and boilers. With these preconditions the research questions are formulated as follows:

1. What are the main challenges in the asset management of steam turbines?
2. What are the benefits of digitalized asset management for steam turbines, and how could digitalization alleviate the observed challenges?
3. What are the technical and practical problems concerning the implementation of digitalized asset management for steam turbines?
4. How could the digitalized asset management for steam turbines be implemented successfully?

1.3 Research methods

The research in this thesis is conducted as a literature review and a case study. The case study is based on interviews with turbine asset management experts. The interviewees include professionals of steam turbine asset management, maintenance, condition monitoring, risk management and automation systems. They work for Finnish industrial and utility steam turbine operating companies, and other stakeholders such as third-party service providers and an insurance company. Many unofficial discussions were had with multiple experts from Siemens Osakeyhtiö. Additional insight about remote diagnostics and monitoring is sought via an interview with turbine diagnostic specialist from Siemens AG. The Finnish steam turbine end users and other stakeholders are in customer and co-operational relationships with Siemens. They were selected in order to form a comprehensive sample of the features, functions and needs that are specific to steam turbines and to the operational environment in Finland. The conducted interviews are used as an input for the follow-up discussion with the same experts.

1.4 Thesis outline

After the introductory section in the Chapter 1, the Chapter 2 explains the theoretical framework of conventional steam turbine asset management, digitalization as a phenomenon, domain specific technologies that are enabling this transformation, and the business model concept. Chapter 3 consists of a case study which examines the digitalized asset management of steam turbines through current set-up, possible benefits and observed challenges which digitalization could offer solutions. Chapter 4 includes discussion based on the findings in the Chapter 3. First, perceived concerns in the implementation of novel digital technologies and business models are discussed and finally the appropriate measures for a successful realization of the benefits are assessed.

2 Theoretical framework

The following section will explain the theoretical background of the most important concepts discussed in this thesis. The first part consists of the model for conventional steam turbine asset management. It is outlined for a better understanding of this specific business that is going through the changes due to digitalization. The second part is an overview of digitalization and its contents. The third part lists and examines a few domain specific enablers of digitalization. The list is not exhaustive but includes some broad concepts that are especially often discussed in the literature related to industrial digitalization and associated novel technologies. Finally, business model concept is defined for a more concrete understanding of the financial aspects of the transformation caused and enabled by digitalization.

2.1 Conventional steam turbine asset management

Asset management is defined as the "coordinated activities of an organization to realize value from assets" (EN 16646:2014). The realization in this case involves balancing of costs, risks, opportunities and benefits. According to International Standard ISO 55000:2014 asset management "translates the organization's objectives into asset-related decisions, plans and activities, using a risk-based approach." Assets are items, things or entities that have potential or actual value to an organization, and the value can be either tangible or intangible and either financial or non-financial. Benefits of asset management include for example improved financial performance, informed asset investment decisions, managed risk levels, improved services and outputs, demonstrated social responsibility, demonstrated compliance and improved organizational sustainability, efficiency and effectiveness. (ISO 55000:2014.)

In this thesis the conventional asset management of steam turbines is divided generally based on the different levels of asset management framework. These are the maintenance activities on the asset portfolio level and condition monitoring on the operational process level. The interrelation between these two is demonstrated in the Figure 1. For example, it is beneficial for maintenance to have operators involved at the operational maintenance level for routine checkups and inspections of degradations and failures. Operation level also provides maintenance level with operating profiles of the assets and Key Performance Indicators (KPI) such as leakage and vibration levels, that help determine required improvements and timing of the activities. Maintenance on the other hand can provide operators with acceptable threshold parameters and operating constraints that help avoid aggravating failure mechanisms. (EN 16646:2014, p. 25.)

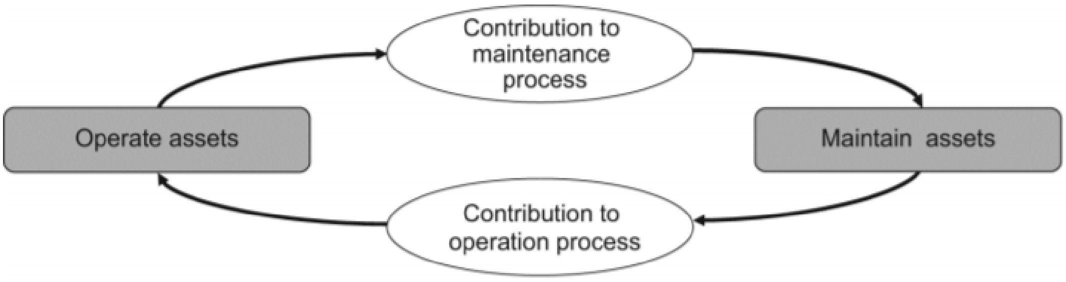

Figure 1. Relationship between operation and maintenance processes. (EN 16646:2014, p. 25)

2.1.1 Condition monitoring

Condition monitoring activities are performed either manually or automatically and are intended to "measure at predetermined intervals the characteristics and parameters of the physical actual state of an item." Monitoring differentiates from inspection as it evaluates changes in the parameters of the item over time. (EN 13306:2017.) Steam turbine condition monitoring aims at detecting malfunction symptoms from changes in performance, temperatures and vibration levels (Ruohola 2014). According to Kauppinen (2018, p. 120) the actual process values that are constantly monitored and registered from the automation system data include

- temperature, pressure and flow rate of the live steam,
- turbine speed,
- power output,
- positions of the Emergency Shutdown Valve (ESV) and control valves,
- axial position,
- relative expansion,
- temperature and vibration of bearings,
- vibration, phase angle, rotor centerline movement and lift of the shaft,
- vibration of the main oil pump,
- temperatures of the lower and upper turbine casings and the exhaust part and
- extraction/bleed steam pressure and temperature.

2.1.2 Maintenance

The standard EN 13306:2017 defines maintenance as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." The actions in general include checking the condition and preventing and fixing damages. The condition and the expected lifespan of the machine are defined by comparing new and old results from inspections executed during basic maintenance.

Damages can be prevented and fixed by either repairing or changing parts, and the appropriate measure depends on the costs, required time and quality warranties offered by the service provider. The future need for spare parts is evaluated during overhauls. Preventive maintenance strategy and well-prepared revisions minimize the amount of unplanned repair works and the total cost. It is important to note that in order to maintain the usability and performance of the turbine, unnecessary outages should be avoided. This is due to large temperature changes that cause wearing in the turbine materials and increase the probability of machine failures.

The Original Equipment Manufacturer (OEM) steam turbine maintenance concept has three phases. These are annual inspections, Minor Overhauls (MiO) and Major Overhauls (MaO). In addition, operational maintenance can be done during operation but because possible revising activities are very limited while the turbine is running, most of the maintenance is concentrated to the revisions during planned outages. Annual inspections should be carried out in 6 000 - 12 500 operating hour intervals or every 1 - 1,5 years. OEM recommends that revisions should be carried out in 25 000 operating hour intervals or at least every three years, and every other being either a MiO or a MaO. Effectively the average time between major overhauls in Finland, however, has been growing steadily and is currently approximately 7,5 years, while the recommended interval is 6 years. The main reasons for this are poor financial situations of turbine operators and their indifference to OEM recommendations. (Ruohola 2014.)

Factors that affect the timing of revisions include the operating and start up profiles, structure, age and operating hours of the turbine. Common reasons for failures can be divided into those which depend on the operating hours and those which are independent of it. The importance of the dependent reasons increases over time. These include normal wearing, corrosion, erosion, creeping, low-frequency fatiguing due to temperature transients, dirt and resulting faults. Time-independent reasons are usually consequences of poor planning, manufacturing, repairing, quality control and errors in materials or in the operation.

Annual inspection
Annual inspections can include functional inspection of control, monitoring and protection systems, inspections during outage and cooling and inspections during operation. Annual inspections last typically 1-3 days. Inspections during possible outage consist of rundown time measurement, turning gear condition and listening to abnormal sounds such as scraping. Inspections during operation includes measurements of specific steam consumption, thermal efficiency, wheel chamber pressures, turbine case temperatures, vibration and expansion levels, oil pressure and temperature and inspection of oil and steam leakages. (Ruohola 2014, p. 35.)

Minor overhaul
MiO is usually carried out halfway between major overhauls and lasts approximately 7-14 days depending on the size of the machine (Ruohola 2014, p. 35). Only the necessary parts are disassembled, and inspections are performed using for example an endoscope. MiO includes all the procedures of annual inspections and additionally inspection of bearings, rotor clearances, alignment and run-out, functioning of ESVs and control valves and their actuators, control and protection systems and oil, steam and gland steam systems. (Ruohola 2014, p. 35.)

Major overhaul
The main difference between MaO and MiO is that in MaO also the turbine casing is opened. In addition to all the procedures executed in annual inspections and minor overhauls, MaO includes dismantling, inspection and cleaning of all the parts, inspection with Non-Destructive Testing (NDT) methods, fault analysis for the possible damages, grinding and scraping of flanges and split joints, changing of the consumable spare parts and the measurement and alignment of all the clearances. After 100 000 operating hours a life cycle analysis is performed, and the expected lifespan is calculated. (Ruohola 2014, p. 36.)

MaO is usually planned to last 4-8 weeks but the average length has grown from 43 days to 75 days. This is partly due to the increased average age of steam turbines but also due to the lengthened intervals between overhauls. Moreover, the majority of overhauls are significantly prolonged from the planned outage time, mainly because of unforeseen findings. 60 % of overhauls with long intervals were prolonged. Seven to eight years can be considered as the critical interval length between major overhauls, after which they should at the latest be carried out. (Ruohola 2014.)

Major and minor overhauls are planned outages, but also unplanned forced outages occur in the case of a failure. Forced outages are usually longer than planned overhauls since they are caused by serious, sudden and often unknown damages that leave no time for preparation and may require extensive repair. Since the costs for unplanned outages are usually very high, the failure analysis and repairing is done only for the affected parts. Forced outages studied by Ruohola (2014) happened in turbines that had been overhauled in 1-5-year intervals, so it is safe to say that the malfunctions were no consequence of overhaul intervals being too long. Instead, major reasons for damages that caused forced outages were poor operational maintenance and condition monitoring, and errors in the process or the materials. (Ruohola 2014.)

Operational maintenance
Some maintenance tasks can be allocated to operators, because they are in a good position to detect anomalies and precursor symptoms of failures. These inspections and maintenance tasks are identified by the maintenance staff or the OEM and the operating staff is recommended to perform them. (EN 16646:2014.) Traditionally plants with a steam turbine have had a plant-specific turbine supervisor who has overseen the management of the turbine.

Operational maintenance includes mostly visual inspections of the turbine and the analysis is based on the strong know-how of the details of steam turbine operation and individualities of the specific machine at hand. Anomalies that may be found during these inspections can be hard to detect via condition monitoring executed from the control room since they are often gradual and small flaws in the system. Due to cost savings and lack of resources, operational maintenance is neglected in many plants and physical inspection is replaced with monitoring of process data.

2.2 Digitalization

Digitalization is the phenomenon of digital transformation of societies, businesses and industries and the improvement of value chain processes through digital solutions. It should not be confused with digitization which is the process of converting information into a digital format. Digitalization is not a new concept, but the lowered costs of sensing, actuating, networking and computing have enabled novel ways of implementing digital solutions and services. (Fitzgerald et al. 2013.)

The first industrial revolution that spanned from 1750's to 1900's introduced innovations such as the steam engine and internal combustion engine. The second industrial revolution spanning from 1900's to 1960's implemented electrification. The third industrial revolution that started in the late 1960's and is still ongoing, introduced digital programming of automation systems enabling high flexibility and efficiency. The fourth industrial revolution, Industrie or Industry 4.0 so to say, and the first revolution to be announced a priori, describes the introduction of Internet technologies into industries through smart connected products and cyber-physical systems. (Drath & Horch 2014.)

The term Industrie 4.0 was introduced by German researchers in 2011 and has since been frequently used to address the transformation that is going to take place as the advanced computing and analytics and the widespread instrumentation of industrial machines become possible and economically viable. Another often referenced concept with a similar technical basis, Industrial Internet, was coined by GE in 2012. Both Industrie 4.0 and Industrial Internet depict more the paradigm change in the way industrial systems and entities are utilized and interconnected and less the influence of new revolutionary innovations. Increased connectivity, efficiency and flexibility based on the concepts of Internet of Things (IoT), advanced computing and analytics will complement the automated systems of the third industrial revolution. These concepts are assessed more thoroughly in the next chapter. (Stock et al. 2018.)

The conversation around digitalization is multifaceted and the diversity of terms and concepts is not yet standardized. Porter & Heppelmann (2014) use the term Smart Connected Products (SCP) that have three core elements: connectivity components, physical components and "smart" components. According to these authors (2014, p. 67) "smart components amplify the capabilities and value of the physical components" and "connectivity amplifies the capabilities and value of the smart components and enables some of them to exist outside the physical product itself."

Other authors such as Stock et al. (2018) and Drath & Horch (2014) talk about Cyber Physical Systems (CPS) that have three levels: physical objects, data models of the object in a network infrastructure, and the services based on the available data. Because CPS and SCP are easily mixed, and their technical fundaments are similar, and due to the fact that the Industrial Internet is continuum of the digital automation systems that emerged in the third industrial revolution, this thesis applies the general term of *digitalization* when addressing aforementioned phenomena, concepts and systems.

Characteristic to these systems, regardless of the name, is that the components, i.e. machines, field devices, individual products, plants and factories can all be connected to a network and communicate with each other. Other characteristic is that they can be made available as data objects in the network, meaning that these systems can have a virtual representation, i.e. a digital twin of the physical object. The digital twin can consist of measured, processed and evaluated data such as 3D models and process simulation models, requirements and function information that can be updated in real time and accessed through various human-machine interfaces for different control options. (Drath & Horch 2014.)

Digital twins augment the corresponding physical machine and form a knowledge base for various services such as remote diagnostics and maintenance, and applications such as solutions using Augmented Reality (AR) and Virtual Reality (VR). AR means a digitally enhanced view of the real world by merging it with additional computer-generated graphics. It can be used through mobile devices or a head mounted visor with additional projector. VR is a computer-generated simulation of the real-life environment which can be viewed for instance through a head mounted display. Additional sensors enable moving and interacting with the simulation environment. Other applications and services that can benefit from digital twins are for example automated robotics and additive manufacturing, also known as 3D printing.

Digitalization can also be assessed through four functions and capabilities it enables. From the least to the most complex these are monitoring, control, optimization and autonomy (Porter & Heppelmann 2014). Figure 2 illustrates the different levels that build on each other.

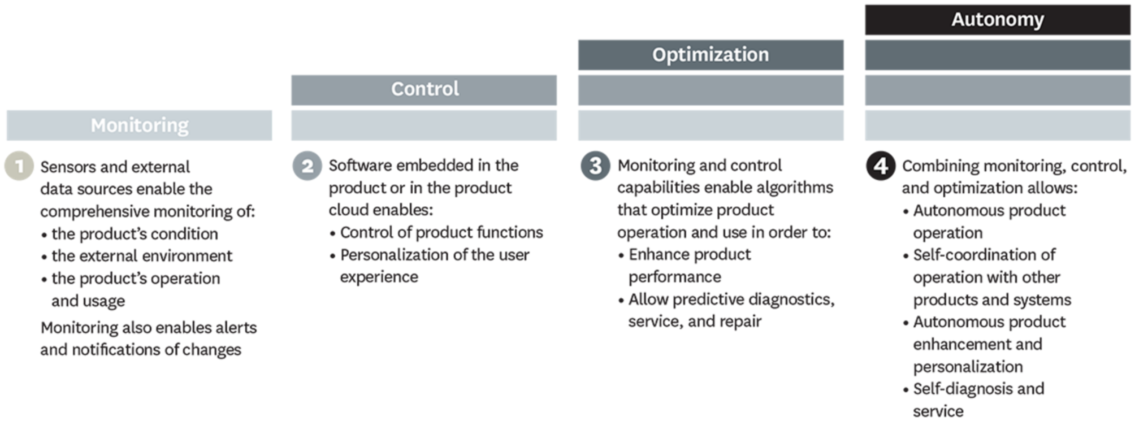

Figure 2. Functions and capabilities of digitalization (Porter & Heppelman 2014, p. 70)

Monitoring
By monitoring the machine and operating condition, safety parameters, external environment, predictive service indicators and other KPIs with data from sensors and external sources, the machine can alert about undesirable changes in performance. Gathering the monitoring data enables businesses to track the operational records which help them better understand how the product is used and what causes faults and damages. This information has valuable implications for machine design, customer segmentation, and services offered.

Control
Remote control with software built in the machine or in the cloud enables the level of performance customization that previously was not economically viable or even possible. Remote control also allows businesses to centralize their control operations.

Optimization
The abundant and well recorded monitoring data complemented with the operation control and advanced computing capabilities enables businesses to optimize performance in multiple ways. Analytics can be applied to both operational and historical data for output, utilization and efficiency improvements. The services can also be optimized with for example predictive maintenance and with more detailed information about fault analysis, required spare parts and overhaul instructions.

Autonomy
Other three levels in combination will eventually enable higher and higher levels of machine autonomy through algorithms that exploit the monitoring, control and optimization data. Possible use cases include self-diagnosis of machine's own maintenance needs and enhanced coordination with other machines and systems. Autonomy reduces the need for operators, improves safety in hazardous environments and facilitates operation in remote locations.

2.3 Enablers of digitalization

2.3.1 Internet of Things

Internet of Things is a term describing interconnected things such as actuators, sensors and humans that all can communicate with each other in order to obtain, control and understand information and to act on it (Diaz et al. 2016). The origin of the term can be traced to the development community for the Radio-Frequency Identification at

Massachusetts Institute of Technology (MIT) in 1999 (Borgia 2014). The International Telecommunication Union (2012, p. 1) has proposed a recommended definition for IoT as: "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies."

Industrial Internet of Things (IIoT) is a subsection of IoT. It is a more limited term that underlines the specific requirements of industrial applications, such as manufacturing or power generation, compared to consumer goods. These are for example low latency, scalability and durability in extreme environments. The basic structure and technologies, however, are the same and both terms are used in the industrial concept. In this thesis the term IoT is used because of its more established and comprehensive nature. (Evans & Annunziata 2012, IIC 2017.)

The vision for Internet of Things is to energy efficiently and economically integrate state-of-the-art technologies, such as Machine-to-Machine (M2M) communication, autonomic networking, cyber security, datamining, cloud computing and decision-making, with technologies for advanced sensing and actuation (ITU-T 2012). M2M communication refers to the communication between entities that do not require direct human intervention. In contrast to M2M the IoT refers to the broader connection of these entities. While M2M targets specific problems in siloed solutions and doesn't generally allow for the broad sharing of data or connection to the Internet, the IoT applications incorporate the distributed monitoring and control applications on a larger scale through data sharing and common governing platforms. (Borgia 2014, Höller et al. 2014 p. 14.)

The general IoT structure can be represented with common building blocks, which according to Höller et al. (2014, p. 69-75) consist of the functional layers and capabilities. These are demonstrated in the Figure 3 and assessed below.

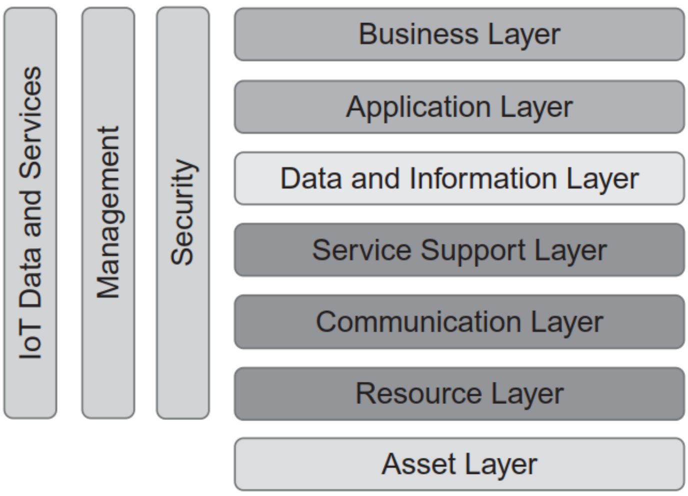

Figure 3. Functional layers and capabilities of IoT solution. (Höller et al. 2014)

Asset layer
The assets are the physical objects and entities, such as turbines, to be controlled, monitored and having digital representations and identities. Assets can also include information of parts of the real world that is of interest to organizations.

Resource layer

The Resource layer provides the essential sensing and actuating capabilities for signal acquisition, as well as the embedded identities for asset identification, such as tags and optical Quick Response codes.

Communication layer

The Communication layer provides the connectivity between the resources and computing infrastructure. The International Telecommunication Union's Telecommunication standardization sector (2012) recommends that the communication layer should provide the networking and transport capabilities, former being the control functions such as authentication and authorization, and the latter consisting of IoT-related control and management information movement.

Service support layer

The support services such as remote diagnostics and software upgrades can be provided from this layer. It is typically executed through a cloud environment in data centers. The cloud environment is discussed in more detail in the chapter 2.3.3.

Data and Information layer

This layer represents the knowledge capture and provides advanced control logic support. Main concepts include data and information models such as knowledge management frameworks which integrate data to information and further to domain-specific know-how.

Application layer

The application layer contains the wide range of IoT applications available and in development. Different industry specific applications relevant to this thesis are discussed in more detail in the chapter 2.3.4.

Business layer

The Business layer integrates the IoT applications to business models and enterprise systems. It also provides the means for data and information access to third party systems through Application Programming Interfaces (API). APIs can be seen as set of routines, protocols and tools enabling different software systems to communicate with each another (Zeng 2018). The business model of IoT and other technologies enabled by digitalization are discussed in more detail in the chapter 2.4.

Management, Security, Data and Services groups

In addition to the functional layers, three cross-layered functional groups can be identified. The Management group deals with the provisioning, operation, maintenance and administration of the IoT solutions. The Security group protects the system, services and generated information through for example authentication, authorization, privacy and network security capabilities. Security measures are required on all layers. Despite the great significance of security dimension in IoT systems and in digitalization generally, the more detailed analysis of the related technologies is not in the scope of this thesis.

Data and Services group is focused on data and service processing steps in the value chain at multiple levels of complexity and either in a very centralized or distributed way. For example, simple data averaging can be done in an individual sensor node and the more sophisticated data mining or data analytics can take place in data centers. Data analytics is viewed more thoroughly in the chapter 2.3.3.
According to Borgia (2014) the general requirements for an IoT system are:

- *Heterogeneity*
  Management of the variety of devices, technologies, services and environments.

- *Scalability*
  Ability to handle the fast-growing amount of resources, data and operations.

- *Cost minimization*
  Optimization of development cost and operational expenditures (e.g. energy).

- *Independence*
  Self-configuration, self-processing, self-organization, self-reaction to events and stimuli, self-adaptation and self-discovering of entities and services.

- *Flexibility*
  Dynamic management and reprogramming of devices or group of devices.

- *QoS*
  Quality of Service guarantees for services and applications regarding for example bandwidth and latency.

- *Secure environment*
  Robustness to communication attacks, secure authentication and authorization, data transmission confidentiality, data and device integrity and privacy.

Currently the three biggest technical impediments for the implementation of IoT systems are the lack of protocol standardization, slow implementation of IPv6 and the power needed to supply the sensors. IPv6 is the Internet Protocol version 6 that uses a 128-bit address theoretically allowing 2^{128} nodes in the network. The supply of IPv4 addresses which have a 32-bit address and approximately 4,3 billion nodes has effectively been exhausted (Cisco 2015). The IPv6 was developed to cover this shortage, as billions of new sensors will drastically increase the demand for new IP addresses in the future. In addition to offering high scalability with unique addresses for all connected things and services, the IPv6 also simplifies network management with its advanced security features and inbuilt network auto-configuration capabilities. (Miraz et al. 2015, Ziegler et al. 2014.)

There are other technologies in development, such as 5G and blockchain, that are trying to answer to the challenges as well. 5G for instance is the next generation of mobile standards being defined by the ITU (2018a). The newest International Mobile Telecommunication standard IMT-2020, the so-called 5G, gives specifications for the systems, components, and elements supporting the enhanced capabilities compared to IMT-2000 (3G) and IMT-Advanced (4G) standards. 5G is set to meet especially the bandwidth, scalability, flexibility and latency requirements of IoT systems (Borkar & Pande 2016). The improvement targets set for 5G are demonstrated in the Figure 4.

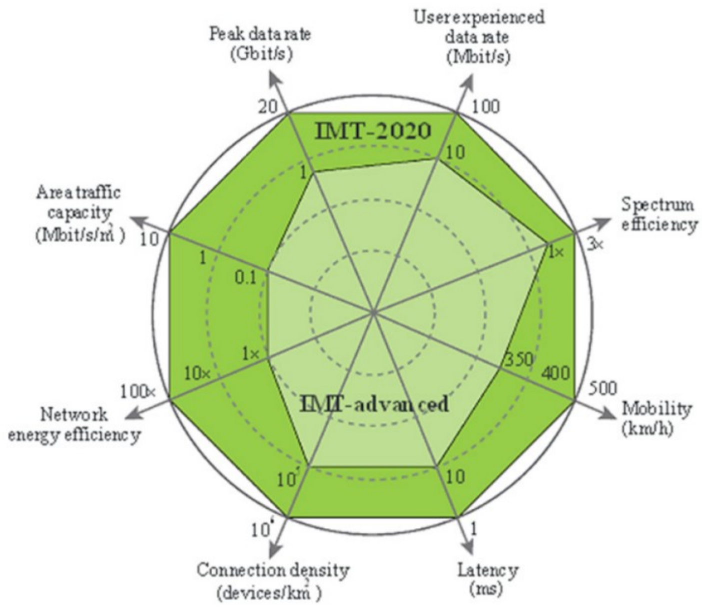

Figure 4. Enhancement of key capabilities from IMT-Advanced to IMT-2020. (ITU 2018a, p. 5)

It is however remarked that while 5G is expected to offer notable benefits by enhancing current digital processes and creating new business opportunities, it requires large investments, and these should be backed by sound business cases. Some of the cases are presented in Figure 5 along with other application and services that can be delivered with current technologies in relation to required latency and bandwidth. (ITU 2018a.)

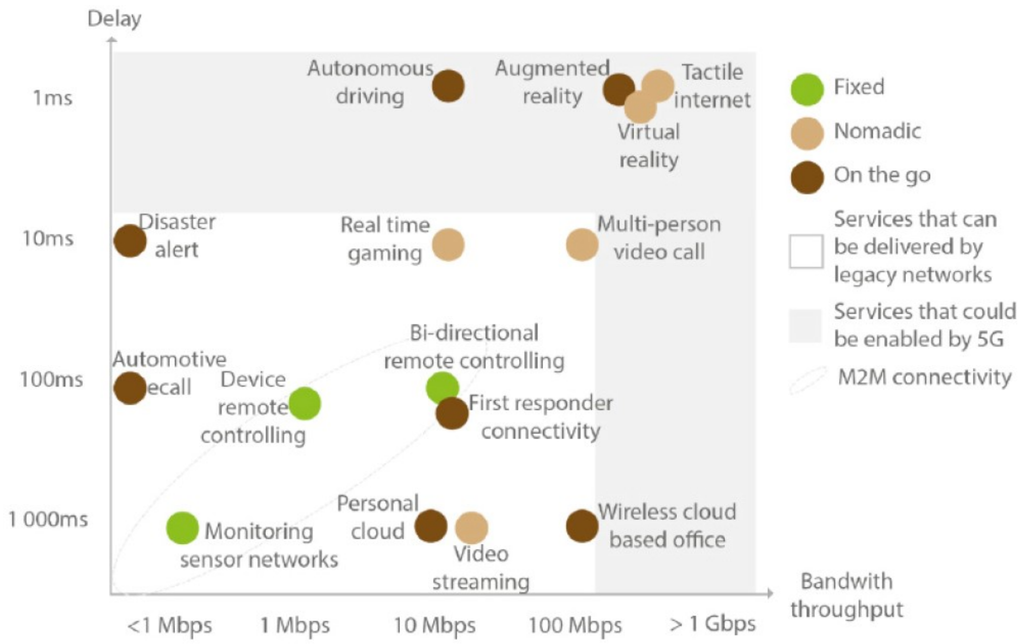

Figure 5. Bandwidth and latency requirements. (ITU 2018a, p. 10)

Blockchain is a cryptographically-linked list of blocks created by nodes in the network. Each block is equipped with a hash which is a code that contains the relevant transaction data, reference to the hash of the previous block in the chain and other varying metadata (Minoli & Occhiogrosso 2018). It is often referred to as a digital, distributed, decentralized and shared ledger, in which transactions are recorded in chronological order. Because the created blocks are distributed on numerous computers and it requires the majority of linked computers to alter the blocks and hashes, it is almost impossible to change once verified data. Blockchain's features effectively make it a disruptive transaction and data management technology that is predicted to be a quintessential part of future IoT systems. Blockchain is set to enhance and simplify the sharing of key relevant data captured from the IoT to the participants in the business network. The technology can be used to conduct transactions between business partners with no intermediaries such as banks or external payment systems. (Miller 2018.)

2.3.2 Cloud computing

Cloud computing is outsourcing of computer services via Internet. It is defined comprehensively by Mell and Grance from the United States' National Institution of Standards and Technology NIST (2011) as a "model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources such as networks, servers, storage, applications, and services that can be rapidly provisioned and released with minimal management effort or service provider interaction." Cloud computing is an essential enabler of IoT solutions and digitalization in general since it utilizes economy of scale (Géczy et al. 2012) and helps connected systems get rid of their limitations concerning for example flexibility, scalability and heterogeneity of data (Diaz 2016). This in turn enables the transition from product-oriented offering to a service-oriented offering (Höller et al. 2014. p. 25). The value model of cloud computing is discussed more in the chapter 2.4. Mell & Grance (2011) categorize the cloud model in to three service models, five essential characteristics and four deployment models.

The three service models:

- *Software as a Service (SaaS)*
  In this service model the customer is provided with an application or series of applications and tools that run on a cloud infrastructure, i.e. the necessary hardware and software. The service provider manages and controls both the product and the cloud. The customer can access the application either through client interface or an API and usually its control over the applications is limited to user-specific configuration settings. The cost for the user is typically determined by the number of licenses owned and the actual usage of the service. Examples of this service model are MS Office 365 and Salesforce.

- *Platform as a Service (PaaS)*
  In this service model the customer is provided with a platform on which it can develop applications and tools and deploy them onto the cloud infrastructure that it does not itself have to manage or control. In addition to providing storage and other computing resources the vendor of the PaaS environment usually supports multiple programming languages, libraries and tools so that the customer can easily build, test, customize and deliver their applications (IBM 2018). User has control over the applications and possibly configuration settings for the application-hosting environment. Example of this service model is Cloud Foundry.

- *Infrastructure as a Service (IaaS)*
  In this service model the customer is provided with processing, storage and other essential computing resources such as networks that the customer can flexibly utilize according to the needs of its middleware and software application. The customer does not manage or control the underlying cloud infrastructure, only the

operating systems, storage and deployed applications. In addition, the user can have limited control of some networking components such as host firewalls. This is the most fundamental cloud computing service and it requires the most IT expertise from the customer itself. Example provider of this service is Amazon Web Services.

The five essential characteristics:

- *On-demand self-service*
  Enable customers to provision and release the computing capabilities unilaterally and without human interaction.

- *Rapid elasticity*
  Enable customers to provision and release the computing capabilities flexibly according to their needs.

- *Broad network access*
  Makes sure that through standard mechanisms these capabilities are accessible from the full spectrum of heterogeneous client platforms.

- *Resource pooling*
  Computing resources of the service provider are pooled in a multi-tenant model and serve multiple customers by dynamically assigning the resources to customers according to demand.

- *Measured service*
  Ensures automatic and transparent control, monitoring and optimization for use of computing resource by leveraging appropriate metering capabilities.

The four deployment models:

- *Private cloud*
  Provisioned entirely to a single organization and its units. It can be owned, managed and operated by a third party, the organization itself or by a combination of both, and hardware can exist off and on premises.

- *Community cloud*
  A private cloud with two or more users with shared interests.

- *Public cloud*
  Such as those offered for instance by AWS and Microsoft Azure. They are provisioned for open commercial use for the general public and exist on the premises of the provider.

- *Hybrid cloud*
  Combination of two or more cloud deployment models. They remain unique entities but are connected through for example proprietary technology that enables data and application portability such as cloud bursting for load balancing between clouds. The most frequently utilized method of hybrid deployment according to AWS (2018) is the extension of an organization's infrastructure into the cloud by connecting public cloud resources to private internal resources.

2.3.3 Data analytics

Analysing the data gathered from machines and processes for automation and controlling purposes is obviously not a new idea. Instead, characteristic to Industrie 4.0, businesses are now trying to gather, and even hoard, and combine data from a multitude of diverse sources in order to derive new knowledge and value and thus new sources of revenue. Novelty in this business model is not really in a new technology, but in that it combines the available technology in a new way allowing the development of services that have not been possible so far. However, IoT systems already generate so complex clusters of data that conventional methods of data analytics are not always capable of utilizing all the benefits of these systems. (Drath & Horch 2014.)

These complex clusters of data that are usually best managed in one platform rather than having it in separate silos creating separate insight are referred to as Big Data (Fouad et al. 2015). In research literature Big Data is usually described with the original three fundamental V's Volume, Velocity and Variety (Laney 2001) and with the later added Value and Veracity (White 2012). Chen & Zhang (2014) and Emani et al. (2015) explain these characteristics as follows:

1. *Volume*

   This feature refers to the vast amount of data that is generated, and which requires a lot of storage space. The potential benefits from the ability to process large amounts of information is one of the main attractions of big data analytics.

2. *Velocity*

   The unprecedented rate in which data streams, accumulates and is processed and structured into records. Velocity refers also to the availability for access and delivery. In other words, it includes the speed of the whole feedback loop, from input to decision.

3. *Variety*

   Variety describes the heterogeneous nature of data sets, formats and sources. Data can be structured like in relational databases, which can easily be processed with conventional data processing tools. Data can also be semi-structured, meaning it does not follow the relational database format, but contain other markers that impose hierarchies of records and fields within the data. A few examples are HTML, XML documents and the raw feed directly from a sensor. Unstructured data has no pre-defined data model and includes for example image, video, audio and text files. (Fouad et al. 2015 p. 3.)

4. *Veracity*

   This characteristic refers to the accuracy and certainty of data and involves cleaning possible biases, noise and abnormalities in it. Uncertainty can be caused by model approximations, duplication, ambiguities, incompleteness and latency among other reasons.

5. *Value*

   Extracting value can be understood as the main objective of collecting and processing large volumes of data. By identifying relationships, hidden or explicit, within the data value can be derived for both analytical purposes such as enhancing human decisions and discovering needs and for enabling new business models.

Data analytics is one of the main tools to refine industries from machine automation to information automation and finally to knowledge automation (Ge at al. 2017). It is basically a knowledge discovery process that consists of pre-processing, modelling, analysing and mining and visualizing the input data for deriving value (Chen & Zhang 2014). The process is outlined in the Figure 6. Data mining can be seen as a set of data analysis techniques with a predictive rather than just descriptive objective that combines statistics and machine learning with database management to recognize patterns in datasets. (Manyika et al. 2011, p. 28.)

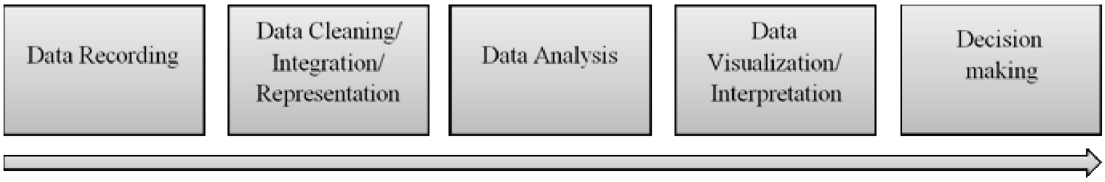

Figure 6. Data analytics process for knowledge discovery (Chen & Zhang 2014, p. 318)

There also exists a huge variety of other computer science and statistics-based techniques that can be used to analyse datasets. Due to limited scope of this thesis only the overview of the relations between different disciplines is presented with a quick explanation of each, including the most relevant subsections.

Artificial Intelligence
Artificial Intelligence (AI) is a subfield of computer science and a notoriously difficult suitcase term to define because of the conceptual ambiguity of intelligence itself. A broad view on intelligence can be formulated as “the quality that enables an entity to function appropriately and with foresight in its environment” (Nilsson 2009, p. 13). AI can thus be defined as “an umbrella term covering a group of technologies that are capable of autonomously performing tasks that, if performed by a human being, would be considered to require intelligence.” Commonly used forms of AI are for example robotic process automation, virtual assistants and machine learning technologies (PwC 2017, p. 2). (ITU 2018b, p. 18.)

Machine Learning
Machine learning (ML) is a subfield of AI. More precisely ML enables adaptivity in AI solutions by designing algorithms that allow computers to evolve behaviours based on empirical data. The objective is to develop systems that can improve their performance even in complicated tasks with more and more data examples and training. ML algorithm performance is strongly dependent of the representation of the given data. ML can be divided into multiple subsections such as computer vision which means automatically learning to recognize complex patterns for advanced classification and analysis, Natural Language Processing (NLP) which combines algorithms and linguistics to analyse human language, and numerous deep learning technologies. (Goodfellow et al. 2016, Manyika et al. 2011, p. 29.) Most of the literature divide ML techniques into three main types:

- *Supervised learning*
  This method is used with labelled data samples and the objective is to predict the correct output or label. Discrete values can be used for classification of process data such as in fault classification. Continuous values can be used to construct

regression models for estimation purposes such as key performance index prediction.

- *Unsupervised learning*
  This method is used with data that is unlabelled or doesn't have the correct output. The objective is to discover the structure and relationships in the datasets. Data visualization, grouping similar items to form groups called cluster analysis and reducing the data to a small number of essential dimensions called dimension reduction are examples of unsupervised learning.

  One specific method that predominantly falls under unsupervised learning is reinforcement learning. It allows algorithms to learn decision making by trial and error. The objective is to find optimal decisions through repetition and by introducing the algorithm with maximum and long-term reward functions that measure how good each state or state-action pair is (Li 2018, p. 9).

- *Semi-supervised learning*
  This method is a combination of supervised and unsupervised learning schemes. Use of unlabelled data with a small amount of labelled data has been noticed to improve the learning accuracy compared to purely unsupervised learning and to a model that would only depend on a small amount of labelled data samples. It is also more efficient since labelling data samples can be expensive and time consuming because it often requires professional human skills and extensive domain know-how. (Ge et al. 2017, Goodfellow et al. 2016.)

Deep Learning
Deep Learning (DL) is a subfield of ML. DL is a set of techniques that enable the automation of the previously manual and laborious feature extraction process needed to transform the raw data into a suitable representation from which the algorithm can learn to detect intricate patterns (LeCun et al. 2015). A term that is frequently associated with DL are the neural networks, more precisely Artificial Neural Networks (ANN) or Deep Neural Networks (DNN), which are colloquially the same thing. ANN are computational DL models inspired by the structure and working method of the cells and neural connections within brains. They are well-suited for finding nonlinear patterns in data and thus for complex optimization tasks. (Manyika et al. 2011, p. 29.) Figure 7 demonstrates a simplified three-layered ANN.

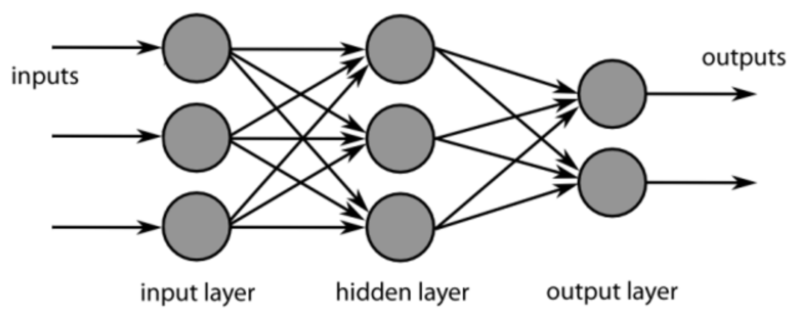

Figure 7. The structure of a three-layer neural network. (Ge et al. 2017)

ANN constitute of input layer that divides the raw input data such as an image or sensor data into appropriate pieces, and several hidden layers of nodes that are used to construct progressively more abstract representations of the data (LeCun et al. 2015). Each layer serves as input for the next layer and finally as an output or activation function (PwC 2017, p. 26). The "depth" refers to the multiple levels of abstraction in the representation, i.e. the number of hidden layers the model has (Mnih et al. 2015). The inputs can be for example the data from individual sensor nodes, the number of nodes in the input layer corresponding to the number of sensor nodes. The more hidden layers and nodes there are in the ANN, the higher accuracy it usually can produce. Complexity and increased depth however increase the learning time and thus the required computational power. (Chen & Zhang 2014, p. 323.)

Each connection in the ANN has an adjustable parameter, a numeric weight. The tuning of weights is called backpropagation. In essence, it is an error correction algorithm that minimizes a cost function, and the optimization of the ANN means finding the global minimum in the cost function by adjusting all weights. In other words, minimum cost function translates into minimum error in the prediction of the ANN. Most of the ANN are designed for supervised learning purposes since the models need sets of training and test data, both of which have to be labelled (Ge et al. 2017). Recent advances in DL techniques, such as combinations of reinforcement learning and ANN, however, are implying that more and more machine learning can be done unsupervised. The evermore increasingly accurate automatic feature engineering enabled by these achievements is significantly reducing the reliance on domain know-how across industries (Li 2018, p. 5). (Ge et al. 2017, LeCun et al. 2015, Mnih et al. 2015.)

2.4 Business model

Digitalization and smart connected things and systems are rapidly transforming industries and their business models, and since business model as a term can be quite broad, it seems appropriate to address the definition. In this thesis the business model framework is formulated following the ontology of for example Bocken et al. (2014), Richardson (2008) and Osterwalder et al. (2005, 2010). Richardson defines business model as the "conceptual and architectural implementation of a business strategy and as the foundation for the implementation of business processes." According to him, it constitutes of value proposition, value creation and delivery and value capture. The framework is illustrated in the Figure 8. Osterwalder et al. (2005, 2010) have presented a more detailed, nine-part division which is illustrated in the Figure 9. A more detailed analysis of business model structure is not in the focus of this thesis, so the following sections are based on the division of Richardson, because it still includes the same subsections as the one based on Osterwalder et al.

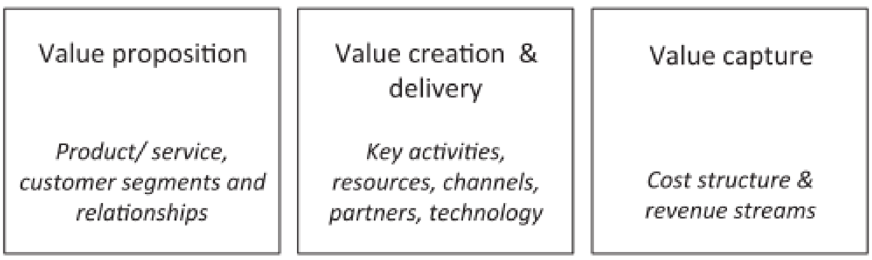

Figure 8. Conceptual business model framework (Bocken et al. 2014).

Borgia (2014, p. 23) argues that conventional business models are not always applicable with highly digitalized products and services or in the broader IoT context, because while data surely opens new possibilities for business, it is owned by users, who decide if they want to share it or not. Important thing for industries consequently is to understand how to monetize IoT services and other solutions digitalization enables, for example through creating novel business models. Next, each section of the business model is briefly explained with a few examples of how digitalization is changing the implementation of them.

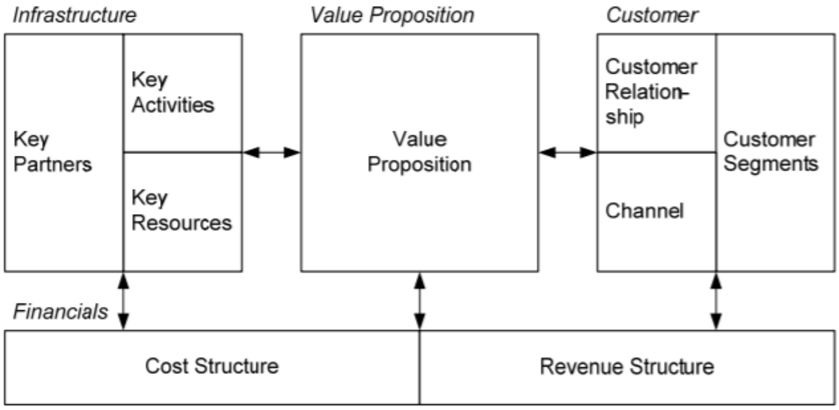

Figure 9. Nine building blocks presented by Osterwalder et al. (2009) constituting the business model (Uckelmann et al. 2011, p. 256).

2.4.1 Value proposition

Value proposition can be summarized in the product or service offer and to different target customer segments and relationships that generate economic return. It tells what the business delivers to which customers and why those specific customers are willing to pay for it. Value proposition defines the basic strategy that wins customers and gains competitive advantage. The core of competitive advantage is operational effectiveness which translates to best practices across the value chain (Porter & Heppelmann 2014). Value proposition should answer why the firm exists, i.e. how the business differs from its competitors and how it is going to compete. Examples of differentiation are cheaper or superior offering relative to competition, lower costs in serving the target customers and niche markets. (Osterwalder et al. 2005, 2010, Richardson 2008.)

The IoT market is still in its infancy stage so it may be hard to see how the competitive advantage and successful business models are reached. The evident lack of standardization in the IoT solutions can mean that competitive advantage could be derived from differentiated technology or data, software platforms or from the ability to provide complete solutions. (Manyika et al. 2015, p. 6.) Data and the derived information are becoming major sources for value creation and thus the value proposition as IoT systems enable additional insight, and right-time analysis and decision-making across different value chains and product life cycles (Uckelmann et al. 2011). As customers become more aware of this, they will become more demanding participants in decisions about what data is collected, how it can be used and who should benefit. Hence, firms will need to communicate clear examples of value propositions to customers to encourage them to share their data. Some of the most important value propositions in digitalized asset management, enabled by the growing amount of accurate real-time data, are the reduced operational expenses, finding new revenue sources, and easier compliance with regulatory and insurance requirements (Hakala 2017). (Porter & Heppelmann 2014.)

One example of digitalized services, cloud computing, enables elasticity in deployment of services and helps business reduce their in-house server stacks and IT service operations, which allows them to focus on their core competencies. As cloud computing also provides the benefits of economy of scale to businesses, data processing tools, enhanced decision support and decision-making systems and information aggregation are set to become widespread. These business process optimization applications are developed for both internal and external use and can be utilized on all levels of organizations. Examples are business processes streamlining, fleet management optimization instead of individual pieces and remote, predictive and real-time maintenance. Companies also vision public and industry specific IoT marketplaces, much in the likeness of for example Apple Store where their businesses could be leveraged greatly, or data sold as a commodity. Such marketplaces, Höller et al. (2014, p. 40) argue however, will unlikely become commonplace before trust, risk, security, and insurance for data exchanges are managed appropriately. (Höller et al. 2014, Porter & Heppelmann 2014.)

2.4.2 Value creation and delivery

This component of the business model tells how the value proposition strategy is implemented and what the sources of competitive advantage are. Value creation and delivery systems include the key resources and capabilities, the organizational value chain activities and processes, and the position in the value network, i.e. the partners and distribution channels that are required for the business to create and deliver the promised value to its customers. The business processes should be allocated so that they reflect the competitive strategy and ensure effective delivery of the value proposition. All the actors in the value creation network in addition to the firm itself, such as the suppliers and distributors and their resources and capabilities, should be able to contribute to that objective. (Osterwalder et al. 2010, Richardson 2008.)

The data-driven ability to remotely monitor the status of machines allows companies to develop closer relationships with customers and facilitates market segmentation, as the different usage patterns can be tracked by customer type. IoT solutions enable a new level of end-user involvement and integration to co-creation processes through for example open and transparent web-based platform concepts (Arnold & Kiel 2016). Provision of individualized products and services requires strong co-operation and is indicated to result in longer-term partnerships with higher switching costs, information sharing and reduced costs for all contributors (Dijkman et al. 2015). Increased amount of individualized information also enables mass customization of products and services, and the consequently improved differentiation from competitors strengthens the competitive advantage of businesses. (Manyika et al. 2015, Uckelmann et al. 2011.)

IoT-based partner networks compensate for unavailable core resources and competencies by providing companies with know-how, hardware, and software in an efficient way. Data management, analysis and mining that allow automated decision-making and centralized remote machine control and monitoring play the key roles. Customers increasingly serve as important collaborative development, engineering and designing partners, and the role of employees changes from operators to controllers and consultants intervening whenever there is a malfunction situation. The changing role of the workforce should be paralleled by appropriate human resource development processes such as interdisciplinary and complementary training. The shift in strategic partner relationships can be initiated with smaller Proof of Concept (PoC) projects. (Arnold & Kiel 2016.)

2.4.3 Value capture

The third concept is the value capture which defines the cost structure and the revenue model. The revenue model specifies how the business charges for its offering or receives money in exchange for its services, for example asset sales, subscription fees, leasing and licensing models (Osterwalder et al. 2010, p. 31). The cost structure can be also called economic model and it covers the costs of production, expenses, margins and other financial factors such as the timing of exchanges. (Richardson 2008.)

The ability to keep close and real-time track of the performance of machines enables business to sell their products as a service. Revenue model can then be for example pay-per-use or licensing instead of asset selling. Providing services instead of products is a major trend in the transformation of digitalization-driven business models. With the Product-as-a-Service model customers can be offered benefits of lower upfront investments, more flexible usage, less downtime and additional services such as updates and maintenance, as the condition of the product is the responsibility of the supplier. A more advanced version of Product-as-a-Service revenue model would be based on service performance such as the uptime. (Uckelmann et al. 2011.)

It is important to note that the Product-as-a-Service models is not necessarily more profitable than the conventional ones, where the customer owns the product. This is especially true with complex and long-lived machines for which parts and service generate significant revenue. (Porter & Heppelmann 2014.) To be more profitable Product-as-a-Service business model requires accurate condition monitoring with measurable performance values that provide a reliable calculation fundament (Uckelmann et al. 2011).

The higher fixed costs for installing the technology stack of IoT system, i.e. software and hardware including sensors, reliable connectivity, data storage, analytics, and security are easily calculated, but the Return on Investment (RoI) has been more difficult to measure, partly because it is complicated to utilize the full financial potential of IoT ecosystems, or the digitalization in general. Therefore Uckelmann et al. (2011, p. 266) argue for clearly defined revenue streams. Several benefits that generate clear revenue streams and minimize the cost structure are expected with digitalized asset management. These can include reduced costs from remote monitoring with the reduced need of field personnel to be dispatched and more efficient spare-parts inventory control. Other examples may be the increased resilience and performance and minimized downtime because of better analysis of machine status and predictive maintenance. Data from failures can also be used to evaluate the validity of warranty claims. (Höller et al. 2014, Porter & Heppelmann 2014.)

3 Digitalization of steam turbine asset management – A case study

The following chapter examines the digitalization of steam turbine asset management as a case study where turbine asset management experts from OEM company, turbine operating companies and stakeholder companies are interviewed. The asset management is divided into three sections: condition monitoring, maintenance and fleet management. Digitalization of these three is analysed in three subsections. The first subsection of each asset management field clarifies the current set-up of digitalization and related practices in that field. The second subsection studies the concrete challenges brought up in the interviews concerning the specific asset management field. In the third subsection possible benefits of digitalization and its opportunities as the solution for the mentioned challenges are assessed. Some of the benefits are speculative, but many of them would be attainable simply if the best practices were followed.

3.1 Condition monitoring

3.1.1 Current set-up

Most of the simpler condition monitoring of a steam turbine happens in a control room that is usually located at the same site as the turbine and the other parts of the process. As the name suggest, also process controlling that is based on the monitoring capabilities is done from the same location. The parameters that are most typically monitored are listed in the section 2.1.1. Other monitored and controlled parameters depend on the use case of a turbine which also defines the required type and scope of the control system. As was explained in the Figure 2 of the Section 2.2 the higher levels of digitalization, i.e. control, optimization and autonomy all build on the monitoring capabilities. Process control for turbines is a self-evident capability and has been available for a long time even with more limited digital solutions. Optimization and autonomy in turbine processes, on the other hand are highly dependent on the possible advancements in monitoring capabilities and improvements in process data recording procedures.

The current level of real-time reactive condition monitoring is in many cases regarded sufficient. Predictive condition monitoring solutions are few but are considered a very desirable target for improvement in both utility and IST plants. Some methods of more complex analysis are available but not implemented into condition monitoring systems for various reasons. An example of such case is the vibration monitoring. For example, the control room typically only sees the numeric levels of vibration, and that is enough information for the operator to change the operation parameters. More complex analysis of the vibration spectrum, the rotor centerline movement and other monitored parameters could ideally reveal the type and cause of damage the turbine has suffered. Often this type of analysis is done by assembling additional portable sensors after some of the values from the fixed sensors have passed the thresholds. The cost of installing more fixed sensors is apparently considered too high and the failures too infrequent to make this analysis continuously available for the control room. Most operators also usually lack the know-how required for any additional analysis.

Another example of a more complex fault analysis that is done but not implemented into real-time monitoring systems is the imbalance analysis. It is required if the rotor-specific critical speed defined by the OEM has changed. This can happen for many reasons, such as change in the rotor mass distribution or scraping of rotor blades. Critical speed is a range of RPMs where the speed resonates with the natural frequency of the rotor. This amplifies vibration, so the critical frequency area is avoided when starting up the turbine, i.e. the turbine is accelerated very fast over it. The analysis requires special expertise and is thus carried out by a third party or the OEM. Usually the turbine operating company wants to do the analysis without opening the turbine, but then the results are approximations. More accurate results would require balancing analysis in a vacuum.

After storing, data from measurements is very rarely returned to. Many plants do not even have the means to access the historical data. Other reason is that older data can be considered outdated and sometimes useless since changing parts also changes the behavior of the turbine. In some failure cases the historical data has been assessed together with an insurance company and other experts to find root causes, but diagnostics software that would have online access to the vibration and automation data are uncommon. Data storages are in many cases hard drives located in the plant site, but also private and on-premise cloud storages are used. The data is often averaged as it gets older. This means that for example vibration data may be measured every millisecond but after a few months it could be averaged over a minute to free storage space. For incidents where the vibration level has changed suddenly, the data can be kept in its original precision automatically for possible future analysis. However, the averaging and automatic preserving of precision both are still under development.

In addition to flawless operation for maximized availability and reliability, most of the desired condition monitoring aims at fewer major overhauls during the life cycle of the turbine because they are the single most expensive procedures in turbine asset management. Steam turbines are delicate machines that require precise adjustments and alignments, and a reliable automation system. Therefore, major overhauls are also always risky procedures, and the demand for opening and disassembly has to be well justified. Many of the system malfunctions occur after a major overhaul because of erroneous reassembly process. This is another reason why steam turbine customers wish for fewer major overhauls during the lifetime of turbines. The lengthening of overhaul intervals cannot however happen on the expense of higher risks. Insurance companies generally follow the OEM maintenance recommendations as the basis for their policies, so the unfounded lengthening would probably increase insurance payments.

3.1.2 Challenges

Many interviewees complained that monitoring systems should be significantly easier to interpret while presenting more refined information. Currently all the procedures and actions have to be learned by the operator through experience. This is not a sustainable situation since the possibilities for learning are apparently smaller than in the past when the systems were designed, and control rooms had more staff. Resulting knowledge gap was elaborated with an example of an experienced operator that would probably be able to describe the procedures behind an ESV movement check, but less experienced operators might know simply that a specific button has to be pushed. Then, if the testing would show malfunctions, the less experienced operator might not have the competence to find the fault and would have to call for outside help. Naturally the experienced operator would have no need for more refined information about the system nor for remote consulting, but the newer one might.

Some of the main challenges with condition monitoring are the lack of information from the measured parameters and alarms in advance of malfunctions. Consequently, operators and maintenance staff lack the means to quickly become well-informed about any given situation. A repeating statement however was that all the necessary data is gathered but it is not exploited to its full potential with further analytics. One reason for this was believed to be that the data use, monitoring and automation systems are developed mostly catering to operator needs and not considering too much maintenance aspect. Even if the objective was to lengthen the turbine overhaul intervals, there usually would not even be a system in place for data analytics that could even in theory enable it.

Predictive solutions are not possible without a comprehensive system that records different trends and analyzes long-term changes. Maintenance activities are of course recorded but it seems to be rare to compile statistics about the works for later reference. These logs appear to exist mainly for financial work order tracking purposes instead of being the content for diagnostic tool development. With data storing the main problem is not the cost but the difficulty of access, poor usability and defining which data is essential for analytics, and hence should stay online for later use. Operators and the plant management seldom have easy access to stored data and if they have, the raw data lacks any meaningful and insightful formulation.

One problem specific to industrial plants is that IST operators often lack the know-how required in turbine startups, outages and other deviations from the normal operation. They are competent with other parts of the process, but the turbine is usually in danger of being neglected or operated incorrectly. Distributed Control Systems (DCS), which plants use to control their processes and the turbine, may sometimes be inadequately equipped with turbine know-how and advanced features. Other times the DCS is sufficiently equipped, but many operators simply are not capable of fully utilizing it. Operators seem to rely a lot on experience, and the possible deficiencies in the operating and monitoring environment have traditionally been compensated with accumulated knowledge. However, startups are for example so infrequent that sufficient experience simply might not accumulate, and plant management has not considered it cost-effective to keep specialist know-how in-house.

Condition monitoring is evidently suffering from an excess amount of alarms from the system and consequent indifference to them. The problem is that alarms from different sectors of turbine systems are so frequent that they and all the other alarms are simply neglected, and the alarm sound is even muted in the control room. This is partly because many of the warnings are triggered when the process values cross the thresholds temporarily but return to acceptable limits on their own. Most of the time this fluctuation stems from natural irregularities in combustion process. Hence, the alarms are manually switched off by the control room staff and this sometimes leads to switching off genuinely serious warnings without actually acknowledging them.

Alarms are rarely completely false, except in new plants where the system configurations are still in need of adjustments. Also, many seemingly mechanical malfunctions can in reality be automation system errors, sensor malfunctions, impurities in sensor areas or connection failures. To make the distinguishability more automatic, the systems can include a rationality assessment between multiple sensors. In some cases, the alarm thresholds simply do not have any logical basis in the practical situation. For instance, there should not be an alarm from low pressure if the machine was only just started. This results in adverse situations where the operator knows that everything is fine if everything is alarming. Alternatively, the alarms can be unnecessary system warnings or notifications with no useful information for the operator. The challenge is to separate the alarms that are caused by normal fluctuation or inherent exceptions and require no intervention from those that warn of incorrect operation or system malfunctions and actually require operator's attention.

In addition to alarm logics, the trip logics can also be incoherent. The operator might not want the machine to have automatic authority to trip based on some specific functions and instead wants to prevent it by changing other process parameters. This however might not always work as it should, since there are causes for trips, such as increasing bearing temperature, which may be impossible to prevent by just changing process parameters. One possible root cause for the disorderly situation with alarm and trip logics may be that it is apparently unclear whose responsibility the determination of safety functions is.

Based on the interviews it appears that the excessive amount of alarms leads to indifference and mistrust to alarm system in general. If the operator cannot distinguish unnecessary alarms from those that indicate real problems, he might eventually switch off even the unusual alarms and ignore all commentaries and explanations about them. There simply should not be any unnecessary alarms for the operators to completely trust the system. On the other hand, the amount of alarms is not always the main issue but alarms in general. IST operators for example usually have a very limited skills concerning the turbine and simply count on its reliability during operation. Since the malfunctions are so rare, IST operating plants have had no significant interest in investing and improving the condition monitoring to be more precise or to have a better connectivity to service provider systems, apart from a few stand-alone remote connections that can be opened case-by-case. Even in those cases the remote service provider often has challenges with diagnosis due to lack of analytic tools. This amplifies the vicious circle where remote diagnostic services for steam turbines are hard to sell to customers which in turn hinders any further development.

Information sometimes does not pass between different shifts of the control room or between the remote control and monitoring center and the plant. Digital diaries are often used but unstandardized and manual logging methods make errors more plausible and sometimes result in the lack of useful information. An example is a repeatedly appearing error and counteractions that are logged only the first time even if the actions varied on other occasions. The purely textual format of diaries and reporting was also brought up as an example of outdated practice because the information is not easily connectible and analyzable.

Lack of trust in cyber security systems and the robustness of firewalls that slows down condition monitoring systems were mentioned several times. One obvious challenge is to combine trustworthy and strong cyber security with agility and user friendliness. The technical theory basis of such cyber security systems is not in the scope of this thesis. Many plants demand a multilevel authentication, such as an SMS authentication in addition to individual login profiles, for the access to their mobile and fixed condition monitoring and Enterprise Resource Planning (ERP) systems. Some customers have two networks, one for internal use and one for external partners to have a login possibility. In some of these cases, the intranet is secured with a multilevel authentication, but the extranet is not. If the extranet is deemed unsecure by either of partners, it blocks any further data utilization and development for digital solutions, because partners cannot exchange any confidential information through it.

The experienced obscurity of data ownership and limits of external use are also hindrances to information sharing and thus broader data utilization. Even though the ownership is very clearly stated to remain with the customer as the original data source, it is still often considered a threat to share anything outside the premises of the plant, even in the case of confirmed data security. Some very small utility energy production plants seem to be an exception, as they have considered potential risks to be very small compared to the benefits of higher quality remote condition monitoring that is enabled by broader data sharing.

The prevalent attitude of many larger turbine operating companies concerning data sharing is caution. Assuring the end users with existing cyber security measures seem to be challenging. One typical example of this is that a customer demands the requests for remote connection to be made via a phone call, after which they plug in the cables manually only for the requested period. Any information that could possibly be used to estimate production quantities is strictly guarded, even when the party requesting data would not be a competitor in any way. Naturally there is more willingness to grant data access to specific machines such as steam turbines for the OEM of that machine instead of automation data of whole plants. Turbine data is quite commonly remotely monitored and diagnosed by the OEM in gas turbine power plants and CCPPs. With utility and industrial steam turbine operators the main hindrance is believed to be the lack of clear business case in a stand-alone project that would justify the investment and the increased risks of data exchange.

3.1.3 Opportunities

One improvement suggestion that came up was a more standardized and automatically formulated digital recording. The logs are usually done manually, sometimes on paper, without any standardized way and are thus harder to inspect and later benefit from. Textual format of diaries and reports should be complemented and categorized with tags, keywords, and error and status codes that would facilitate automatic diagnostics and data connection. One simple example case is an outage information record which could include the timing, reason, the duration of the rundown, from what power level it started and how it was managed. The immediate benefits of such records may not be self-evident, but a more widespread implementation could bring about new possibilities in the form of for example Case-Based Reasoning (CBR) solutions. CBR system could automatically find a reference case with similar KPIs, error codes and other circumstances. Based on them and how the previous situation was handled the system would be able to give suggestions and predict the findings and root causes of possible malfunctions.

The lack of a single trend monitor that could be viewed on a required scale when needed was brought up. This trend monitor could depict a collection of automatically formulated essential trend lines such as vibration measurement data, temperatures and pressures of the turbine and heat exchangers, RPMs, the power output and preferably some derivative indices like efficiencies and other KPIs. Such values are rarely calculated from the trends retroactively if it has to be done manually. More standardized and automated logs in a single location would facilitate the inspection and further automated analysis of changes in the operation.

Overall, it is harder to analyze raw data than for example precalculated indices, relations and coefficients combined from a set of measurements. Long-term trends might reveal small changes that would be impossible to be detected just by monitoring individual values which could very well still fit inside the preset thresholds. Monitoring systems are currently good at detecting flaws that have already occurred, but less capable of finding the flaws beforehand. The rarity of steam turbine malfunctions implicates that it may not be profitable for turbine operating companies to keep fully in-house the special turbine expertise required for the predictive analytics. Consultation and required expertise for these occasions should therefore be obtained through a specialized service provider. Remote diagnostic services could include for example remote guidance in planned and unplanned outages and in startup situations, advanced long-term diagnostic reports and early warnings in case of sudden malfunctions. Such services could enable the predictive and preventive features of turbine condition monitoring without compromising the competitiveness of companies.

Most of the remote service solutions would require continuous data exchange and for some, such as the online remote guidance with shared view and remote-control options, the connection could be opened case-by-case. Since turbine occurrences are rare but require special know-how almost every time, the benefits of remote guidance given by a turbine specialist were believed to be great. Such specialist would have simultaneous access to both turbine monitoring data and OEM data. Continuous remote monitoring from a manned monitoring center was not believed to be as beneficial. Instead operators could rely on better data-analytics which would also automatically notify them early enough when outside specialist would be needed.

Different applications for diverse use cases exist in the condition monitoring environment. These are sometimes provided by several different companies which is why the applications have variable interfaces and communicate poorly with each other. This multitude of different subsystems is sometimes considered a nuisance and is potentially hindering the optimal data utilization. Common IoT platforms and operating systems are possible alleviations for the disadvantageous diversity of condition monitoring applications because they have the ability to combine the access to many different applications through one portal. Such solutions can simultaneously streamline security requirements and simplify the visualization, thus lowering the threshold for data utilization in cases where too many application interfaces were already determined troublesome.

It was also stated that the operator especially in industrial plants should have a very simple and intuitive access to turbine control and maintenance systems in their monitoring environment. One example was an interface based on Piping and Instrumentation Diagrams (P&ID) along with better labeling and tag numbering so that the connection between documents and machines would be easier. A more customer-oriented approach was demanded to operational sequences and instructions, meaning that the information should be more targeted for the operator so that they are not flooded with unnecessary information.

Based on the challenge of redundant alarms one clear opportunity with digital solutions is the development of a data analytics tool that would learn to filter those alarms that are triggered by the natural fluctuation from the rest. Further development of such optimization instrument could be extended through ML to detect also other kinds of anomalies from the natural operational data and suggest maintenance measures and changes to operating parameters for safer and steadier running. Simple, yet still arduous solutions to redundant alarms is the manual programming of conditional expressions in the system, such as a delay before the alarm would be triggered to get rid of the fluctuation-based alarms. This would require the combination of domain know-how, practical experience in the control room and programming skills. Also, the need for categorization of alarm criticality was expressed. This could be done both with color coding and by sounding the alarm only in the most crucial situations while less important ones would be presented only on screen. The analysis of possible chain reactions between different malfunctions would help operators intervene proactively. Modern automation systems have tools for alarm categorization, but these could be used much more effectively in projects.

Some innovative methods for advanced remote condition monitoring are solutions that detect changes in visual and audio signals around the monitored machines. For instance, AI might be able to detect steam leakage from thermal camera feed with image analytics or a malfunctioning pump by listening to the specific sounds of machines in their normal operation. Some of such solutions are currently being tested and could be further developed to automate fault detection and targeting, and to enable the findings to be made earlier. As the cost of AI solutions reduce, more and more applications become available. ML together with domain know-how could be utilized in connecting different operating circumstances to reoccurring faults and findings. For instance, the fluctuating operating profile of an IST in a batch production plant or a turbine in a peaking power plant might have inconspicuous associations with increased corrosion or other damages in the materials. Particularly if the turbine was not initially planned for it.

The increased knowledge from advanced diagnostics could be used in condition monitoring as suggestions for optimal operational parameters, and in life cycle assessments and long-term trend analytics as a kind of “stress calculators” that could indicate how much lifetime specific operational parameters consume. Similar applications are already implemented in many gas turbines. Other use case could be predictions for the list of required maintenance works in the upcoming major overhaul. However, it was underlined that merely the more automated connection of different monitored parameters would be a simple and yet beneficial improvement at least for turbine operators, because it would yield a more refined overview of changes and other occurrences. The connection is already possible but would have to be done manually and would therefore be unnecessarily laborious and slow, and thus provide only hindsight.

AR, VR and other simulation solutions were mentioned as possible tools both for educational purposes and for improved control and understanding of the process. Especially the capability to simulate startups and other special operation such as emergency situations in advance was regarded as an enhanced safety feature in itself. The price of AR, VR and other simulator applications was compared to the cost of external power demand during an outage of an IST and generator caused by incorrect startup and was considered minimal. The cost of remote consultation service would also be almost insignificant compared to the price of the electricity that would have to be bought in case of an internal outage. In other words, a comprehensive cost-benefit analysis would likely show that ensuring startup safety pays off regardless of the solution. Unplanned outages are of course always extremely expensive, but preventive solutions are more vague and harder to define in other cases than in startups.

Without more advanced diagnostics in condition monitoring systems, for instance optimal timing of overhauls will not be possible. According to one remote diagnostic specialist, the lengthening of intervals between major overhauls based on advanced condition monitoring has already been introduced. There have also been cases where additional sensors and monitoring have enabled extended lifetime of machines without increasing the insurance costs. It is therefore justifiable to say that advanced condition monitoring solutions can make longer overhaul intervals possible without compromising steam turbine reliability and availability. One enabling factor has apparently been the remote diagnostic services that utilize both rule-based algorithms and the know-how of steam turbine expert, instead of just relying on automatic system analytics software. Based on the interview with one insurance company representative there is no excess margin in the insurance prices. Thus, better condition monitoring solutions would not yield cost reductions in insurance payments. They can however help proving that risks even in longer overhaul intervals are still under control.

Other important benefits that could come from advanced condition monitoring are shorter outages due to reduced number of unforeseen findings that prolong the overhauls. This and the ability to more accurately price the maintenance help reducing the financial risks associated with overhauls. Apparently, many steam turbines that have acquired remote diagnostic services are also provided with suggestions for optimal operational parameters for best durability. The influence of suggestions depends strongly on the operational profile. An IST with fluctuating profile is bound to wear faster than a utility steam turbine with couple of fixed load points. However, as predictive fault analytics and digital twins with real-time thermodynamic simulation capabilities develop, these recommendations can become increasingly automated and more effective. Such solutions could help avoid damages before the next planned outage and thus lengthen the overhaul intervals.

3.2 Maintenance

3.2.1 Current set-up

The big contrast between utility and industrial steam turbine operators became very obvious in the interviews. Utility customers generally have a lot more know-how about the turbine maintenance, and therefore the service needs also differ. Industrial steam turbine operators for instance require more support with the operational maintenance, startups and fact-finding in small malfunctions in addition to overhauls, whereas utility operators seem to need support mainly in cases where the turbine has to be opened, i.e. major overhauls.

The maintenance of steam turbines is only moderately facilitated by digitalization. One obvious reason for this is the highly manual nature of maintenance since it consists of material inspections and conventional repairing and manufacturing. Hand tools are often required, and dirty environment is not considered suitable for tablets, computers or other delicate devices. Current progression is substituting some maintenance with monitoring, but due to limited monitoring capabilities this can lead to some small flaws to go unnoticed for longer period of times which in turn can lead to larger and more severe damages in the turbine system. This neglect of proper operational maintenance was in fact mentioned to be one of the biggest problems in maintenance of ISTs. They are seldom neither the main focus nor area of competence in industrial facilities and associated operations are thus easily reduced in the name of cost savings.

Turbine overhauls are timed mostly based on the operating hour equivalents and other factors as was explained in the Section 2.1.2. Equivalent hours consist of the actual operating hours and additional hours that are added to compensate the wearing resulting from cold, warm and hot startups. The compensation works as a preventive measure and as such, this maintenance concept is not based on the actual maintenance needs. Therefore, it is called *interval-based maintenance*. In the future, more precise and insightful long-term diagnostics and condition monitoring with predictive analytics might enable *condition-based maintenance*. Currently however, tools that could help timing turbine overhauls based on actual the needs are limited to basic level condition and vibration monitoring. Furthermore, the outages are so costly and require so much planning that the malfunction would apparently have to be significant and thus easily noticeable to affect the pre-set intervals.

ISTs are not generally included in the annual overhauls of industrial processes. Main reason for this is that cooling and opening of the turbine per se usually takes longer than the annual overhaul of other sections of the industrial process combined. Even though process steam can be produced without a turbine by using reduction valves, it does not generate electricity and the isolation of the turbine from active process would be expensive and complicated. Even though smaller ISTs would cool faster, the cost of arranging even a minor turbine maintenance has been considered to outweigh the financial benefits of a more stable running. Faster cooling with pressurized air has also been tried and observed to be potentially very profitable, but its material effects are still studied.

All maintenance that requires turbine disassembling is usually done with the consultation of the OEM or other service suppliers. These service contracts are offered based on the requirements in the customer's tender, and with public actors based on the Act on Public Procurement and Concession Contracts. In addition to price, the tendering references usually include previous experience with turbine overhauls and the duration of the outage. In major overhauls the promised duration typically does not match the reality as was stated in the Section 2.1.2. This is partly because the referencing system itself. It is not beneficial to prepare for everything, and the longer promised duration yields less points in the bidding. Service contracts for steam turbine maintenance are usually purchased case-by-case due to expected lower total cost compared to long-term contracts. With public actors, additional incentive for this is to avoid the rigid public tendering process which is mandatory in the higher price category.

Most of the maintenance work itself is still done manually and recorded first on paper and later digitally. Worker operations are tracked to some extent with timecards, but for the Time and Materials (T&M) based invoicing they are still often logged on paper sheets due to inadequate accuracy and connectivity of customer's and service provider's timecard systems. AR and VR solutions are still so expensive to utilize that obvious business cases are missing. For example, remote consultation that is often brought up as a possible use case for AR-based enhancement is generally performed via phone calls which is not considered too troublesome nor in need of expensive development. The same applies to AR-enhanced manuals where instructions are embedded into the machine. Fitters and maintenance staff, even when requesting special consultation, are skilled enough to manage with current systems. This however seems to apply only to utility steam turbine operating companies. The IST customers have more need for all kinds of consultation and might benefit from added visual help.

Steam turbine maintenance is spare part centric, albeit not as much as the gas turbine maintenance where most of the parts have shorter and very strictly defined lifespans after which they will certainly start to break. Steam and gas turbines have similar spare part supply chains, but the less delicate nature of steam turbines leads to more repairing and fewer parts being changed regularly. Other difference is the lower price of steam turbine spare parts which in turn yields smaller return on investment to more efficient spare part management. Many turbine plants have their spare part inventories for example in Excel files or embedded into an ERP system with automated quantity tracking.

3.2.2 Challenges

Major overhauls are prolonged mainly because of unforeseen findings inside the turbine. Findings that require a lot of additional work that was not originally scheduled are discovered at the latest halfway through the overhaul outage. The reason is that most of the inspection work is visual or at least requires total disassembly of the turbine and cleaned surfaces. Depending on the use case of the turbine, the status of other turbines the company possibly owns, and the nature of the service contract, this prolonging can either be very expensive or it can be cheaper to exceed the deadline than to pay extra to meet the schedule. For an industrial steam turbine operator, the process steam demand determines the schedule, but for a utility operator it might be that the turbine would anyway be in standby after the overhaul is finished due to low district heat and power demands.

If big flaws are discovered, it usually happens too late for the schedule to hold. To avoid the outage prolonging, these flaws should be discovered sooner or even in advance of the outage. The heart of the matter is apparently not a lack of sensors in the turbine but the need for better analytics of the existing measurements to find the root causes for malfunctions. This lack of quick firsthand knowledge about occurred malfunctions leads to longer response time and delays the problem solving. Reoccurring problems in some specific turbine models have been able to be prepared for in advance. The knowledge about such reoccurring problems however rarely meets if it is not documented by the same organization every time.

It was noted that sometimes when a remote maintenance and fact-finding is utilized, the remote specialist lacks the means to distinguish between mechanical malfunctions and sensor and control system errors, which prolongs the maintenance process. Another reason for long response times is the small size of local service provider organizations with enough domain know-how. Because the skillful workforce is scarce, there is a risk that all field service personnel are unavailable in case of a sudden malfunction. Resulting costs of production interruption can be immense.

Utility steam turbine maintenance customers typically have a lot of know-how on their own and the demand for outside workforce and expertise is less frequent than with industrial steam turbines. With gas turbines the demand is even larger, because the machine is so much more complicated. In many cases, IST customers lack the competence and resources to neither define their actual maintenance and operator needs nor to perform cost-benefit analysis on advanced service concepts and spare part inventories. Consequently, the threshold for performing smaller but still necessary maintenance work is high, which apparently often leads to neglecting those works all together. Utility turbine customers’ expertise is broader but seems to be limited especially in material know-how. Turbine operating companies often use third-party specialists because they do not trust the OEM in being absolutely neutral in its assessment of service and spare part needs. Additional consultation of course adds to the total cost of maintenance.

A few customers identified the low quality and delivery delays of some documents provided by the OEM as a reoccurring issue. The use of subcontractors in making of documents was suspected to have resulted in more errors. Unclear or unbinding pictures have the potential to unnecessarily complicate otherwise simple maintenance work. Although, customers also admit that many of their plant operators have poor skills in English which can have the same effect. Fitters and technicians often lack the means to assure the correctness of documents and manuals they are using which delays maintenance works.

The lack of clear maintenance instructions, lack of connectivity between different records, and the scattered and incoherent information of the previous changes and maintenance history have been identified as some of the main challenges in steam turbine asset management both in the interviews of this thesis and by Vitie (2017). Changes and maintenance are recorded by the one who performs the work, be it a third-party service provider, the OEM or the customer itself. Usually all of them have their own recording methods and systems which are rarely connected. Modifications during maintenance can for instance be logged on a maintenance quality document written by a third-party service provider, but it is the customers responsibility to manually record the reported data into their ERP system and to notify the OEM. Information about pending maintenance works are scattered and hard to find, and the documentation suffers from the same dispersion. The widely varying age of implemented solutions further complicates any efforts to synchronize different logs. Many steam turbine components are custom-manufactured, and the lack of consistency in documentation and information exchange has in some cases lead to manufacturing incorrectly sized parts due to information about dimension changes not reaching the manufacturer.

Due to cost savings and professionals retiring, much of the maintenance work has to be done with fewer resources. This means for example that one has less time for planning and documenting which results in lower quality maintenance. One experience is that reports get shorter and more general, pictures are less organized, and with less monitoring of maintenance needs the overall asset management of the steam turbine suffers. Some existing digital solutions that are implemented in order to facilitate maintenance tasks such as documentation and reporting, are considered painfully slow to use. For some users with less experience with digital applications the interface itself might be the hindrance. Another cause is the robustness of cyber security which slows the connection to these systems. Apparently, it is also sometimes ambiguous which of the many systems the documents should be exported to. On the other hand, the underuse of documenting tools and lack of thorough reporting in general seems to have been a topic for discussion for decades. This indicates that the experienced rigidity is just a reason among others for the slow utilization rate of said systems.

Even the most conventional systems could produce useful documentation if the reports were done more carefully. This would not necessarily call for novel documenting tools, even though they could help with the attitude change that is apparently required instead. Even standardized reporting forms cannot help if the worker is reluctant to fill all the parts. Reports were suspected to be sometimes intentionally left incomplete, especially in regard to root causes of observed malfunctions. Knowledge protection between companies and among field service personnel is apparently still deep-rooted.

Another system that suffers from slowness is the work order system for correct and smooth budgeting and invoicing of maintenance works. This might result in customer’s assets being tied for harmfully long time. One explanation may be the one mentioned earlier that customer's and service provider's timecard systems seem inadequately accurate and connectable. Other reasons are the strict and multilevel approval chains, and manual operation tracking and invoicing processes. The same rigidity applies also to the purchasing orders and the spare part supply chain. Unstandardized ordering methods, lack of technical domain know-how in the customer's purchasing organizations, and outdated information in the ERP systems all affect the efficiency and swiftness of the supply chain. Some example causes for these problems are the insufficient or incomplete information in the e-mails used for purchasing, and varying structure and content demands for lists and pictures.

A big nuisance seems to be the difficulty to connect between customer's and supplier's different material numbers used for the same component. Development for more standardized and connected spare part catalogues and more automated purchasing is hindered by the customizable nature of steam turbines. For gas turbines these systems are more widespread thanks to their fairly homogenous structure which allows economy of scale. Some delays also appeared in updating the turbine setup information after modernizations and overhauls so that the preparations for next maintenance were impeded. The use of e-mails as the main supply chain communication tool was mentioned to amplify this problem but was seen to have many benefits as well.

Some of the plants in this case study have their ERP systems available through mobile platforms. In there they can access and upload for instance maintenance documents, new and old alarm notifications, photos, travel expense claims and work orders. The use of these mobile applications consistently suffers from slowness and sometimes occasional crashes even if the applications were very simplified. Apparently, main reasons for this problem are the rigidity of the VPN connections and obligatory authentication procedures used by these companies.

3.2.3 Opportunities

First step to fewer unforeseen findings is the better connection of control room diaries concerning frequent alarms, information about the source of the fault and the ensued overhaul measures. Additional diagnostics should be considered for easier narrowing down of the location and root cause of minor and major malfunctions after they have occurred. Currently determination of required maintenance actions is delayed by the simplicity of monitoring solutions. This could be improved by remote technical support with the combination of domain, context and analytics know-how, which would be unprofitable for the turbine operator to keep in-house due to infrequent demand. Service models are for instance remote guidance of maintenance actions and remote fact-finding based on the monitored data. The quick reaction time for this kind of service would necessitate a more comprehensive remote access to the turbine system data, and some type of long-term contract so that the service would always be instantly available without a separate purchasing. Remote support at short notice together for example with aforementioned startup simulation capabilities would decrease downtime and thus increase productivity and availability of the turbine.

The possibility to share for example site reports and fact-finding documents between the supplier and customer instantly was considered to be an improvement to current e-mail-based exchange. Some interviewees identified the need for a more standardized document that would also include more information that the customer has to report, such as working hours, maintenance activities and findings, and tools and parts that were used. Joint documentation would reduce duplicate work. Similar benefits can be gained with tools that enable real-time collaboration between the customer and the service supplier. In a simple form this means a shared view and simultaneous editing of the same documents such as P&IDs and reports. A more advanced solution would be a common portal for the project management where the project status, responsibilities for different tasks, previous discussions of all participants, contact details, schedules, deadlines etc. could be clearly laid out, coordinated and accessed. Such portals had been observed to lower the threshold for communication between participants, increase transparency, and help organizing the project better compared to e-mail-based co-operation.

A centralized access for instance to datasheets, circuit diagrams, maintenance documentation and exact physical xyz-coordinated locations of devices in the site was called for. The real-time editing capability to record changes and repairs directly to a centralized system simultaneously as they are being performed was deemed essential in order to prevent errors and overlapping. Currently this information stays in a separate report unless someone manually registers it to every relevant system. This was noticed to result in confusion of which document was the latest version.

The demand for connected, centralized, simple and real-time information applies to all sections of the steam turbine asset management. Digital twins could be implemented in maintenance even if the real-time thermodynamic simulation capabilities would not be included. This would allow intuitive and illustrative use of the turbine asset management system. It could for example automatically notify about required maintenance and instantly update recorded changes and document edits to all associated systems. In the future digital twins may also facilitate the evaluation of the effects of different operational actions in advance, if they are supplied with accurate process simulation.

Most of the desired features could apparently already be enabled in new commissions if a comprehensive and compatible engineering software were implemented straight from the beginning. This would lay the foundation for an all-encompassing asset management system, which in turn is the basis for digital twin capabilities. For older turbines such systems are harder to assemble but IoT platforms and operating systems might have the potential to facilitate this development. They could work as the connecting factor between the sensors, the database and the necessary applications.

A few features considered beneficial for digital documenting tools include added connectivity between different applications and real-time interaction between different team members inside these applications. The future development of data sharing and co-operative applications available in the ERP system depend partially on the same problem of unsecure extranet utilized between customer and supplier, that was defined in the Section 3.1.2. A minimum data connection between customer and service provider can work as the starting point for further advancements in collaborative and consultative operations.

Furthermore, the challenge with slow connection to ERP systems could be overcome with faster broadband connections on plant sites, as well as with implementation of 5G networks due to its enhanced security features and inbuilt network auto-configuration capabilities. Faster and more agile connections also enable advanced remote service solutions. These include for instance AR visualization and other ways of personal mobile gear utilization. For example, AR and shared view could facilitate remote consulting and guidance. Currently such applications are still so expensive that they are not desirable. However, the reducing price will likely make them more appealing.

The supply chain could be made more agile if some of the middlemen and excessive steps can be removed. In the future, whenever value or data is transferred and these transactions are recorded, blockchain-based smart contracts could be used to secure and simplify the process and make it more transparent. Delays in the delivery are typically caused by intermediaries who manage the approval of shipment paperwork, but blockchain and other solutions might be able to eliminate the need for these types of intermediaries from the supply chain. Also, if customer's spare part inventories were directly connected to manufacturer's ERP system, the purchasing order could be instantly logged to the factory.

The main challenges with this development are the aforementioned different styles of part coding, i.e. the dissenting material numbers, and the remaining need for consultation about the machine maintenance requirements. The latter is often provided via e-mail simultaneously with spare part order management and thus could not easily be streamlined or automated along with purchasing. The development of a faster spare part supply chain for steam turbines might not be as profitable as with gas turbines, but the need for improvements definitely exists, nonetheless.

Other spare part related opportunity lies in the better asset tracking all through the supply chain. The customer would benefit from knowing more precisely where the ordered parts, such as turbine blades and tools needed in major overhauls, are going and when they will arrive. The same possible benefit of tracking would of course also apply to all maintenance in general, as it would make the scheduling more accurate and help with time management. Tracking would not necessarily have to stop at the plant site gates but could instead continue until the part was fitted. This would prevent parts going missing, which apparently sometimes happens.

In the future parts can be 3D printed and repairs provided with the help of additive manufacturing. Once again, the steam turbine parts would presumably provide less return on investment than their gas turbine counterparts, but cost reductions can bring this technology closer to broad utilization. As was stated, unforeseen findings are a big reason for very expensive prolonging in major overhauls, and additive manufacturing with its mobile and agile capabilities might be able to alleviate this problem. Thus, it would definitely be beneficial to develop cheaper, quicker and more mobile and flexible refurbishment technologies. One of the main challenges facing the additive manufacturing in turbines however concerns the very specific material requirements.

3.3 Fleet management

3.3.1 Current set-up

Fleet management is a term that describes fleet level operations and planning, such as finding synergies derived from combining operational optimization, condition monitoring and maintenance activities between different plants of the same organization. In this thesis fleet management concerns only the benefits of steam turbine fleet management. Other kinds of fleet management would typically include for example optimization and timing of operation of different plants using different fuels with different operational costs. The steam turbine fleet management includes but is not limited to optimal timing of outages, life cycle assessments, and combination of maintenance resources, condition monitoring resources and spare part inventories.

Fleet management is especially common among utility turbine operators such as municipal energy companies with multiple power plants and Combined Heat and Power (CHP) plants with varying fuels. Outages for major and minor overhauls have long been scheduled in the most optimal way between plants. Other companies seeking benefits from fleet management are for example pulp and paper producers, which usually operate multiple plants including many ISTs. Fleet management can be done completely in-house, or it can be outsourced to some extent. There is a clear trend to lean own resources across the industry and throughout the turbine asset management activities. This leads to more outsourcing to OEM and other third-party specialist.

The main difference between utility and industrial steam turbine operators, turbine-wise, is that for the former, energy is the end product and turbines the main asset. Their operations are determined by the district heat and electricity demands. Hence, the most beneficial approach seems to have been and probably continues to be the fleet management of entire power plants. Due to this, utility companies seem to have kept a lot of turbine know-how in-house. For IST operating companies on the other hand, turbines are just a small part of the process and total assets. Steam turbines are considered to be long-lasting with fairly little maintenance. Therefore, IST asset management has been in the focus of budget cuts for a long time. In-house and outsourced fleet management of ISTs can be particularly beneficial because of the consequent lack of skillful workforce with steam turbine domain know-how.

It is not common to have shared condition monitoring systems between the steam turbines of different plants without having the whole plant in remote control or monitoring. Globally those steam turbines that are remotely monitored are often parts of CCPPs and the main focus of the fleet management is in the gas turbines. Usually energy companies with multiple steam turbines in their fleet have a shared maintenance team for their plants. These teams may be provided with vibration data and other relevant information which help them perform operational maintenance and inspections. For industrial organizations with multiple ISTs in their fleet, these teams centrally manage the assets concerning rotating machinery, i.e. handle the technical aspects of maintenance purchases, and audit and inspect maintenance execution.

The conventional way of IST fleet management is already done with minimal resources, so the companies rarely do maintenance work itself. Instead they need to rely heavily on the service providers and third-party consultants. In recent years, efforts have been made to centralize and synchronize the spare part inventories and provide maintenance teams with more comprehensive mobile access to them. Apparently, the ERP systems and spare part inventories both still have plenty of development potential.

3.3.2 Challenges

Operational planning is only as good as the data it is based on, and it seems that turbine fleet managers lack the means to assess their life cycle costs reliably. All management practices including monitoring, operation and maintenance are based on a long experience. For example, changing and repairing intervals are fairly standard, and are often based on the accumulated knowledge about reliable lifetimes of different parts. This information seems to be challenging to translate into optimization algorithms and predictive tools, especially with widely altering parameters of steam turbines.

Currently steam turbines in different plants are still very siloed systems and companies rely on competent people to transfer their experience forward and among their fleets. However, since the economic situation has become tighter, and with fewer skillful people in the workforce, turbine operating companies are forced to find synergies to become more competitive. Furthermore, new employees do not have the same time to accumulate their experience as the skillful workforce that is now increasingly retiring. For these reasons, companies are trying to find ways to prevent the consequent knowledge gaps with novel business models and various digital solutions.

The simplistic use of text format diaries and records hinders the development of connected and analyzable central records that would better combine knowhow and experience from different plants with similar problems. As long as the information is exchanged via phone, and diaries with records of occurrences and solutions are not labeled and compiled, knowledge will remain scattered and incoherent. Capabilities that could exchange important information about the turbine between essential systems are still out of reach for most turbine fleet operators, and everyone keeps on struggling with same problems separately. Some steam turbine operating companies currently utilize third-party fleet management software, but apparently many of these are very niche solutions.

Plants and steam turbines inside fleets have widely different ages, utilize many different systems and have been commissioned using different methods and engineering software. It was also pointed out that changing parts changes parameters and almost all steam turbines are unique with varying sets of parameters. Because of the customizable nature and widely varying features of steam turbine systems their manual fact-finding requires a lot of domain know-how and experience. Old machines might have materials that are not even used anymore. These factors significantly complicate efforts to manage steam turbine fleets and to develop more advanced digital services.

3.3.3 Opportunities

Basically, all opportunities that can be listed for condition monitoring and maintenance apply also to fleet management as well, if the actions can be centralized. Benefits of centralized data storages for instance have been experienced to be great. A single database for all operated and monitored plants offers the advantage of cost-effective reporting systems and enables different kinds of data utilization. Especially the fault analysis could benefit a lot from such solutions. Experiences from centralized gas turbine databases are by and large very good. Problems can be multi-faceted and complex but compared to turbine fleets of specific operating companies the global fleet of an OEM is big and those problems may be reoccurring.

The movement and storing of information for example about similarities between alarms the different plants have dealt with should be more automated and utilizable. As these experiences have been exchanged via people, so could the data and information be exchanged directly between turbine systems. More and better connected and labeled cases might also facilitate and speed up fault analysis process and conclusion making by giving service providers the tools to develop advanced diagnostics using for example AI and ML solutions. Other example is the aforementioned CBR system that would take advantage of labelled and connected reference cases for quick and automatic fault analysis and suggestions. By connecting their turbine data to a centralized database, steam turbine operating companies can share its benefits while also contributing to it themselves. Such databases hold the potential of maintaining and scaling up accumulated experience and domain know-how, and thus alleviate some of the problems concerning the shortage of skilled labor in related industries.

Fleet management of steam turbines can bring synergy advantages for companies with multiple plants even if they are not continuously connected to any large external database. The ERP systems and spare part inventories are still utilized in a siloed way, meaning that different plants and assets could be more synchronized with each other and with the manufacturer's and other service providers' systems. It was emphasized that centralized ERP systems are already in place and often even have many of the desired features, but their more connected and synchronized utilization still has great potential because of the current underuse. Some interviews mentioned the opportunities of AI implemented in ERP systems to facilitate the management of spare parts and acquisition of services. Possible applications could include more automated criticality assessment and life cycle cost analysis that would work as the basis for purchases and other appropriate actions.

Several interviewees expressed their need for better fleet management tools for holistic life cycle cost analysis and life cycle assessment. The desired tools would give steam turbine operating companies a better understanding of different effects, risks and accumulating costs of their decisions. Such applications would greatly help in negotiations because currently these companies feel uninformed. This sentiment likely makes customers very cautious of digitalization investments which may not be as easily financially justifiable as some conventional asset investments.

Digital solutions, such as remote diagnostic capabilities, enable the outsourcing of some parts of the steam turbine fleet management. This would be particularly advantageous for IST operators, because their domain know-how is focused so heavily on the other parts of the process, and the demand for turbine expertise is so infrequent. Outsourced fleet management of the steam turbines might free resources for the more critical functions and allow especially IST operators to focus on their core competences. It might also improve the quality of operational maintenance, reduce the risks of incorrect operation and negligence, and minimize the response time for consultation. The so-called pay-per-use model for digital products and services might be greatly facilitated by blockchain solutions, which would in turn make those services more desirable. Performance-based contracting has also been considered one of the future opportunities that might come with the broader implementation of blockchain technology.

3.4 Summary

Table 1. Challenges and opportunities in steam turbine condition monitoring.

Condition monitoring

Challenges	***Utility***	***IST***
Knowledge gap between experienced and inexperienced operators		x
Lack of information and alarms in advance of malfunctions	x	x

Insufficient maintenance recording and tracking systems	x	x
Data systems hard to access and utilize, raw data not useful	x	x
Operators lack the startup, outage and anomaly know-how		x
Condition monitoring systems lacks advanced features	x	x
Excess amount of alarms	x	x
Alarm thresholds are not sensible	x	x
Differentiating between system and mechanical errors	x	x
Differentiating between unnecessary system notifications and errors	x	x
Lack of diagnostic tools in remote connections	x	x
Information goes missing between shifts	x	x
Rigid cyber security systems slow down data utilization	x	
Systems for external data exchange not secure in customers terms	x	
Obscurity of data ownership and limits of external data use		x
Opportunities		
Automatic digital records, tags, labels, keywords and status codes	x	x
Trend view of KPIs and derivative indices instead of raw data	x	x
More intuitive and user-friendly interfaces		x
Central access to documents, system data and location information	x	x
Alarm filtering with advanced solutions, such as machine learning	x	x
More personalized information for the operator		x
Conditional expressions to reduce the amount of alarms	x	x
Alarm criticality categorization	x	x
AI solutions to detect changes in operation and condition	x	x
Connecting circumstances to reoccurring faults with machine learning	x	x
Suggestions for optimal operational parameters	x	x
Assessment of remaining lifetime of turbine	x	x
Predictions for the list of required maintenance and parts	x	x
Suggestions for operational maintenance activities		x
Remote guidance for anomaly situations, outages and startups		x
Automatic notification when remote service is needed		x
Optimal timing of overhauls with long-term trend analytics	x	x
AR/VR solutions for training purposes		x

Table 2. Challenges and opportunities in steam turbine maintenance.

Maintenance

Challenges	***Utility***	***IST***
Unforeseen findings that are found too late in the overhaul	x	x
Lack of analytics to know which parts need to be changed or repaired	x	x
Errors and outdated information in reports and documents	x	x
Incoherent documenting and reporting systems	x	x
Ensuring the correctness of documents is hard		x
Unclear maintenance instructions	x	x
Lack of connectivity between different records and ERP systems	x	x
Scattered and insufficient information of the maintenance history	x	x
Scattered information of pending maintenance works		x
Slowness of mobile ERP and documenting applications	x	
Underuse of reporting tools	x	x
Work order systems are inaccurate, inadequately compatible, and slow	x	x
Lack of turbine know-how in customer's purchasing organization	x	x
Lack of connectivity of OEM's and customer's purchasing systems	x	x
Supply and approval chain slowness	x	x
Opportunities		
Real-time editing capability to documenting systems	x	x
Better connection of control room diaries to maintenance and condition monitoring systems	x	x
Maintenance systems that better enable the analysis of measured data	x	x
Remote guidance of maintenance actions		x
Remote fact-finding based on measured data	x	x
Real-time interaction and data sharing between project team members	x	x
Joint documentation to avoid duplicate work	x	x
Common project management portal for clear information lay out	x	x
Adoption of 5G for smoother security features and application use	x	x
Connection of customer and OEM spare part management systems	x	x
Supply chain tracking for spare parts	x	x
Additive manufacturing for quick response time in case of unforeseen findings	x	x

Table 3. Challenges and opportunities in steam turbine fleet management

Fleet management		
Challenges	***Utility***	***IST***
Lack of skillful workforce		x
Lifetime of parts hard to assess, life cycle costs hard to estimate	x	x
Lack of good operational planning system for turbines		x
Older turbine systems designed for siloed operations	x	x
Lack of central database and records to accumulate knowledge	x	x
Information exchanged via phone leaves no records of discussions	x	x
Different ages of turbines and systems inside fleets		x
Nicheness of implemented third-party fleet management systems	x	
Lack of cross optimization of different OEMs' know-how	x	x
Opportunities		
Centralized databases for cost-effective and easy reporting systems	x	x
Fleet data to databases for case-based reasoning and analytics	x	x
Better connection and synchronization of ERP systems	x	x
AI solutions in ERP systems to make suggestions, categorize and assess criticality of spare parts	x	x
AI solutions in life cycle assessment and life cycle cost analysis systems to help in decision making and to work as the basis for purchases	x	x
Remote capabilities that enable outsourcing of some operations		x

4 Discussion

This chapter of the thesis is divided into two sections. The first one discusses the specific concerns that the turbine operating companies, the OEM and other stakeholders have, and which are believed to be the main hindrances for the better and broader utilization of digitalization. These concerns are assessed with the same structure as was used to study opportunities and challenges of digitalized asset management for steam turbines, i.e. condition monitoring, maintenance and fleet management. The second section analyses the ways to answer to the concerns, so that the observed challenges can be alleviated, and the benefits attained.

4.1 Concerns

4.1.1 Condition monitoring

Even the most diligent digital condition monitoring or operational maintenance would not easily substitute the overhauls where the turbine is opened. Nonetheless, when executed properly they might prevent smaller flaws from escalating. A spokesperson for an insurance company noted for example that one problem with justifying the skipping of minor overhauls with existing sensors is that often the correct functioning of ESV is nearly impossible to authenticate without opening it during an overhaul. Cracks, twists and mechanical wearing are generally hard to find without visual inspection after the turbine has been opened and cleaned.

Severe malfunctions rarely result from a single failure, and with every new failure in the essential systems the risk of a forced outage multiplies tenfold. Therefore, it was emphasized that the prospective advanced turbine condition monitoring systems would have to unquestionably demonstrate how the operations have improved so that it would be justified to arrange fewer major overhauls during the lifetime of the turbine. The complexity of malfunction chain reactions was also considered to be the main hindrance for better filtering of unnecessary alarms. Automatic criticality assessment would be challenging to make absolutely reliable. The risks in situations where important alarms go unnoticed under the excess amount of less crucial notifications has to be weighed against the risks of more automated alarm filtering.

Turbine plants control and monitor their processes through a DCS and they are usually very tied to that interface. A specific problem in industrial plants is that even though the turbine can be controlled through a DCS, there is a lack of features for advanced turbine analytics in those systems. The focus is often so heavily on the industrial process that it is not considered sensible to switch into other systems. The Turbine Control Systems (TCS), which is practically always supplied by the OEM of the turbine itself, is connected to DCS with an open loop. A closed loop would compromise the confidentiality of the OEM's special expertise and using a TCS from another supplier would make it impossible for the turbine supplier to give performance and availability guarantees.

Open loops are one reason why some turbine customers complain about their incapability to understand flaws and reasons for malfunction in boiler and turbine safety automation systems. OEM of course does not want to disclose the system source codes to their customers. Implementation of self-diagnostics in those systems would probably not increase operators' own repairing capabilities but would facilitate remote diagnostic services and thus speed up the fact-finding. Operators do not want additional interfaces with the TCS but connected information to existing systems. Technically this can be done but would require double work in the configuration of automation systems. With some older machines the control systems would first need to be equipped with a level that can make the remote connections. These works can significantly increase the total costs of digitalization.

The main reason for the modest amount of implemented advanced diagnostics is not however in the connection details, but instead for example in the scarcity of clearly demonstrated business cases. This in turn is partly due to slowness of occurring changes, i.e. the long time it requires for long-term trends to indicate significant changes in the operation profiles. Because long-term trend analytics would require a long time to yield any results, PoC projects have been difficult to organize. PoC projects related to digital steam turbine asset management have apparently suffered from the “chicken or the egg causality dilemma”. This means that it is argued whether business case should be stated before the project or if it can be demonstrated during the project. This also complicates the sharing of costs, if it cannot be indicated in advance who benefits and how.

Automatic advanced condition monitoring solution are hard to develop because the know-how is challenging to turn into algorithms, according to one remote diagnostic specialist. Instead, the specialist had great confidence in rule-based diagnostics and algorithms that are used together with steam turbine experts. The diagnostic services combine domain know-how with for example cloud computing in digital twin simulations without trying to automate all aspects of condition analytics. This approach has apparently been much more successful and beneficial. Then again, some diagnostic reports provided by such service organizations were criticized for their abstruseness. The reports are apparently too difficult to comprehend for people who are not some level of steam turbine experts themselves. The reports should state clearly enough if and how something is broken or operating incorrectly. A separate turbine specialist should not be needed to interpret the provided information.

One challenge with the broader utilization of remote diagnostic services for steam turbines seems to be that they have been offered mostly in combination with long-term contracts without properly addressing the issues with increased commitment. Stand-alone connections on the other hand are apparently harder to make profitable. Some steam turbine users might consider it as a downside that they would need to be connected and tied to one service provider. Not being able to simply buy a licence to a diagnostic software could create a higher threshold for the implementation of advanced diagnostics. Separately built connections are also more expensive than most of the automated data analytic tools.

In addition to technical and practical challenges, OEMs lack strong financial incentives to develop such solutions for steam turbines. It seems to be more profitable for them to keep overhauling steam turbines with current settings, than to offer for instance predictive fault detection diagnostics. Increasing durability of the turbine would reduce the need for maintenance services, which currently constitute a big part of OEM’s revenue streams. Reduced demand for maintenance services would have to be compensated with increased demand for condition monitoring services. This would also have to be more advantageous for both the customer and the service provider.

Current competition with short-term service agreements and case-by-case acquisition of solutions makes it harder for condition monitoring service provider to keep their diagnostic service organization profitable. Third-party software developers might not suffer from the same disincentive, but on the other hand usually lack the domain know-how. Third-party service providers have neither the exact manufacturing information nor the design for different thermodynamic conditions. The operational optimization would therefore be much more challenging for them compared to OEMs.

Another related reason for the lack of advanced features in turbine condition monitoring systems, provided either as remote services or as a software, was believed to be simply the lack of focus and resources. This applies to both supplier and purchaser organizations, even though growing focus and investments to digitalization from the purchaser side have been observed. Increased focus is due to shortage of skilful workforce, which is forcing steam turbine operating companies to optimize their organizations. On the service provider side, the steam turbine business has the risk of lacking investments and therefore focus, partly because of the financial disincentives mentioned earlier. If the steam turbine OEM is involved also in gas turbine services, the risk is even higher because gas turbine business is usually more profitable. Gas turbine asset management services are well-supported by long-term contracts, and their more standardized nature scales up any found benefits.

4.1.2 Maintenance

Some of the problems experienced in steam turbine maintenance seem to stem from the same contradictions that disincentivize the development of better condition monitoring solutions. Services and products that would speed-up overhauls and make customers more capable of performing fault analysis and maintenance by themselves, would naturally reduce the need for these as a service. Often OEMs that work also as service providers would be the most capable of developing these solutions, but naturally have no financial incentives for it. As such, they are typically not a part of OEM product and service portfolios. For example, the current maintenance business model does not optimally encourage OEM to invest into expensive solutions, such as additive manufacturing, that would facilitate and speed-up overhauls.

Harsh competition for maintenance projects has also led to strong know-how protection in order to maximize OEM’s bargaining power. This and the customers’ cautious mentality with data exchange hinder the development of advanced features in maintenance systems. For instance, stand-alone data connections for remote consultation and maintenance might be suspected to be inadequately beneficial compared to data security risks if the same quality of service can be gained with phone calls and by dispatching specialist to the site. On the other hand, the latter is likely more expensive for both the turbine operating company and the service provider. Remote services would also require more know-how and information sharing between the service provider, customers and subcontractors. OEM’s reduced bargaining power would probably have to be compensated with alternative business models, such as long-term service agreements.

IST and utility steam turbine users usually choose the supplier which they know to have a large, local and quickly available aftersales service organization. The required know-how in turbine asset management services is so scarce that customer organization have been forced to make do with less than they would like to. Despite the lack of turbine know-how, IST customers do not generally make long-term contracts, mainly because the demand for conventional maintenance is thought to be too infrequent. Some customers voiced a concern about being too dependent of one supplier if such agreements were made. Long-term contracts also face the problem of possible inflation which would have to be taken into account when defining the prices.

The problem with short-term contracting is the tedious process from justification to tendering to the final approval that must take place every time anything is purchased. Short-term contracts are on the other hand believed to result in a lower total cost in the long run due to short contracts having more competition compared to all-encompassing long-term contracts. Such presumptions however could not be based on financial calculations because opportunity costs are generally not determined comprehensively. For instance, the cost of unoptimized operations with less competent staff would be very hard to define. The continuous competition for service contracts also inherently leads to valuable information being less exchanged between business partners.

Some maintenance professionals had the opinion that applications for digital documentation and training would have to be more than just substitutes for the conventional methods. This is because the need for steam turbine maintenance is so infrequent that in order to justify the investment, they should bring additional value. Even the mobility of these tools would not necessarily be enough in itself. Supposedly, if the documenting tool had no other additional qualities, it would continue to be easier to just document maintenance works afterwards on a computer or on paper instead of doing that on a mobile device while working. The challenge with more standardized and jointly created documents is of course that the service suppliers usually have many customers and all of them have different ways of working and documenting, so the standardization would be complicated. Other challenge in the standardization is naturally the competition that leads to differentiation and know-how protection.

Even if the real-time process simulation capabilities are disregarded, digital twins with centralized, connected and interactive access to information seem to be difficult to develop for the diversity of steam turbines. This concerns especially the older machines that may not even have comprehensive digital blueprints in the first place. Many of the newer plants and turbines lack these features as well, even if they have been commissioned using some engineering software with suitable digital twin development capabilities. Apparently, such engineering software have so many different versions and offer so many customized modules that even if the same software was used by different suppliers, they would not necessarily be compatible. For example, one supplier might design a plant with the same software as another supplier uses to engineer the turbine system of the plant, but that same software might not be utilizable as the asset management system after commissioning.

The benefits of implementing a comprehensive engineering software in the asset management are apparently not emphasized sufficiently in the original investment processes, especially in IST investments. This was also assumed to apply to other sections of acquisitions, such as spare parts and additional features in DCS and ERP systems that facilitate usability and maintenance. If the customer, who is planning the investment, has no clear picture of potential gains and opportunity costs for additional investments, he just tries to do without. Transparent criticality assessments of spare parts and asset management systems were mentioned to be vital part of the investment process as well. Additional investments are apparently not evaluated sufficiently partly because customer's purchasing and Operations & Maintenance (O&M) organizations are not co-operating in an optimal way.

4.1.3 Fleet management

Utilization of old and real-time data from different steam turbines for problem case referencing would in theory be very beneficial, but currently seems to be extremely complex. The customized nature of steam turbines makes the development of any AI-based case referencing and analytics really challenging. Evidently, steam turbines are so diverse and multifaceted machines that the connection between different cases to find common nominators is limited. Especially ISTs were mentioned to be so tailor-made, that the number of reference cases usable for teaching the machine learning algorithms would practically be one. The remote diagnostics specialist elaborated that OEM might have decades worth of archives of field service and fact-finding reports but similar failures in similar conditions would still be very rare. Two identical machines could suffer from very different vibration problems due to for example imperfection in the manufacturing.

It appears that CBR systems are easier to be developed for gas turbines. Gas turbine operating profiles are similar with each other and the machine structure is fairly standardized. CCPPs and gas turbine plants are also often commissioned by fewer suppliers, so the data collection has traditionally been simpler to organize. Hence, the centralized data base utilization for gas turbines plants, and even jet engines for that matter, is much more advanced than those for steam turbines.

The development of steam turbine fleet management services and products might be hindered by some of the same concerns as the advanced condition monitoring and maintenance solutions. One challenge is the complexity of data collection. Fleet management and cross optimization of OEMs' domain know-how would most likely require better connection of service provider, customer and third-party systems. A more continuous data exchange between the parties would also be necessitated. At least in the current business model increased sharing of know-how could pose a risk for OEMs who have to preserve their competitiveness. Knowledge sharing inside companies is simply a matter of management decisions, but information exchange between organizations is regulated by the competition regulator. Particularly strict rules apply to larger machines that are included in the public electricity markets. Useful information cannot therefore remain with only few parties so that competition would remain fair. This was suspected to disincentivize some development projects that would require more open disclosure of data.

Field service organizations are optimized throughout the industry. Many turbine operating companies desire lean own resources and thus outsource operations that are not in their core competence. Service providers determine the size of their personnel based on how much asset management services are required. It was elaborated that keeping sufficiently large local organizations becomes unprofitable without the "base load" for predictable work demand. Case-by-case acquisition of maintenance services appears to exacerbate this problem because it results in uncertain demand for services. In the current situation, turbine operating companies might not be able to outsource their fleet management operations if fleet management service providers consider it unprofitable to keep sufficient personnel employed. The applied business and partnership model should instead incentivize organization structures that are capable of meeting the customer expectations.

There are limits of how many turbines a single remote service expert can serve and monitor. Apparently, a sufficient number of remote asset management service personnel is easy to reach during the daytime. However, during nights and weekends the remote service reliability is more challenging to meet. This is also one reason why such service organizations are less frequently local. Field and remote service organization require a "critical mass" of turbines, so that the costs and revenues are balanced. Global centralization helps reaching the needed number of customers because it is not as tied to specific regions as the local organizations. The centralization of fleet management can also alleviate problems with finding substitutes when each turbine is allocated with a specialist. Nonetheless, if too few local field service personnel are employed in the regions, customers start to prefer other more agile service providers with shorter response times.

In the interviews many companies with steam turbine fleets brought up concerns about obscure data ownership limits, poorly communicated location of remotely measured and stored data and use cases for its utilization. Novel data utilization business models are considered risky and feared to result in losing control over one's own data. Companies sometimes have suspicions of the reliability of firewalls and are concerned that unauthorized third parties gain access to their key figures. This experienced uncertainty concerning data exchange clearly reduces companies' urges to test and experiment with some fleet management solutions and remote services in general. Another hypothesized cause for this could be the scarcity of competent and innovative people with sufficient skills in digitalization and associated systems. The lack of reliable means to life cycle assessment and cost analysis might have the same effect.

4.2 Successful implementation of the digital strategy

Interviewees observed uniformly the service providers' ability to keep sufficient personnel to be in the best interest of steam turbine operating companies as well. The desire for quickly available steam turbine field service specialists who would have access to digital diagnostic tools was highlighted numerously. Such personnel were seen as complementary to existing third-party service organizations, not as displacement. Co-operational approach was estimated to be less risky in regard to customers' dependence of the OEM, than complete outsourcing. Consultation with fast response time in cases of alarms and for instance unsuccessful startups was considered to be at least an equally viable, if not even better, option with automated alarm filtering and operational suggestions. Customers prefer human guidance to automated diagnostics. Providing the consultation as a service instead of as an automatic control system feature would of course require larger remote service organizations, which would cost more. Therefore, the demand would have to be big enough for revenues to outweigh the costs.

Often a seemingly mechanical turbine malfunction is in fact a system malfunction. For example, in the case of an unsuccessful startup sequence, the root cause is usually in the automation system and not in the turbine itself. Therefore, remote diagnostic service organizations should include a sufficient automation system expertise as well. The combination of such cross-domain know-how was observed to still be in need for improvements.

Interviewees on both the purchaser and contractor sides emphasized that digitalization projects for steam turbine asset management need more long-term persistency and diligence. In order to carry these processes through, focus and responsibilities should be well communicated and delegated. Otherwise they will inevitably become vague and the progress will stall. This applies to development and implementation of advanced condition monitoring solutions as well as documentation and other asset management tools. For example, normal overhaul intervals are so long that without consistent reporting the important knowledge cannot accumulate. Teams that have been assembled for co-operative problem solving, such as predictive fact-finding for reoccurring failures, have in some cases dispersed due to everyone having other more urgent tasks and no one having the long-term responsibility. Sometimes the executives might not even see these efforts beneficial enough. Those who are appointed to advance digitalization projects at the same time with their other job, may be forced to weigh the tasks against each other. This artificial contradiction was believed to be disadvantageous to progress and should therefore be avoided.

Especially IST customers often run out of resources to verify their service needs themselves. Therefore, constructive and interactive long-term partnerships with the OEM and other service providers could be mutually beneficial. They would also reduce overall risks of steam turbine asset management. The most convenient maintenance, consultation and training service concepts and auxiliary asset management systems should all be determined in close collaboration between partners. The mechanism for cost formulation should also be more transparent and present the opportunity costs better for well-reasoned decision making. It was emphasized by multiple interviewees representing turbine operating companies that the customer is willing to pay for the good reliability of operations and predictability of costs. The importance of good field service organizations with fast response times as a criterion for choosing the service and system provider was highlighted. Advanced remote diagnostic and consultation capabilities should therefore be implemented in the digital strategy as essential parts to optimize the cost structure and efficiency of field services.

One prediction about the possible cost structure changes was that the utilization of advanced diagnostics systems would enable longer turbine warranties. This prediction was rationalized with statistics about reducing cost of sensors, measurements and cloud computing. Lower prices are allowing service providers to offer the same solutions to steam turbine operating companies that have traditionally been profitable to implement only in gas turbines and CCPPs. The reduced risk level due to longer warranties might allow steam turbine operating companies to make more farsighted investment decisions. This would also facilitate investments that suffer from indefinite payback periods.

Warranties are made for example for two years and commonly include different guarantees, such as the turbine availability guarantee which is very much desired by turbine operating companies. It typically excludes planned outages of the operating plant as a whole and a few other exceptions. Some interviewees expressed their optimism regarding the redefinition of the cost structure in digitalized asset management systems. Others saw challenges especially in the sanctioning practices, because the sanctions possibly paid by the supplier are nowhere near the potential production losses in unplanned outages. Compensations will most probably remain as the responsibility of insurance companies, but small bonuses could be paid in cases where for instance performance has exceeded the liabilities. The change of responsibility in some specific asset management expenses during warranties was not considered impossible if the condition monitoring reaches sufficient accuracy.

Advanced condition monitoring could yield life cycle cost reductions through fewer major overhauls during the lifetime of a turbine. Other easily expressible savings can come from shorter and optimally timed maintenance if the diagnostics can indicate which part of the turbine need to be targeted and when. Investments to such systems can be hard to justify with only a hypothetical prevention of a hypothetical malfunction. Ruohola found in his thesis (2014) that longer overhaul intervals are linked to prolonging of major overhauls. Therefore, if the interval lengthening from the current critical length of 7-8 years is desired, a lot of emphasis should be put on optimizing maintenance durations.

It seems that stand-alone remote diagnostic services are not offered more often due to difficulty of demonstrating enough financial benefits and defining the payback periods and ROI in those projects. If stand-alone remote diagnostics were offered for free during warranty period of a new machine, it would be much more attractive for the customer to purchase and test them. After warranty periods, when the feeing would begin, a stand-alone remote diagnostic service might become too unattractive for the customer to make any investments to. Even so, one diagnostic service specialist was confident that if their expertise was better included in the negotiations, customers would see the benefits of their services and more frequently purchase them as well.

Aftersales services are typically offered afterwards and not simultaneously with the commissioning project of a new turbine. Reasons for the separation could be found on both the purchaser and contractor sides. Apparently, a common practice for steam turbine customers is to purchase a new machine and consider auxiliary services only after the warranty ends. Customers' project organizations are typically separated from the service organization. They are strictly focused on acquiring the new machine with an optimal cost and going below budget can for example be linked to the bonuses. The inevitable future maintenance needs are not their responsibility because the life cycle costs are usually not a part of the evaluation criteria. The result is that the life cycle services are many times left out of consideration when tendering for a new machine.

On the other hand, offering the aftersales services for free during warranty period would reduce the profitability of sales projects. This increases the opposition in contractor side because new machine sales projects already have very small margins. Thus, additional project cost for example from connection configurations and hardware installing are refused in order to maintain profitability. Currently the services are not included in the new machine offers if the purchaser does not specifically ask for them. To change this, the higher level of management would apparently have to make a decision in principle to include remote diagnostic services automatically in new machine offers. In contrast, new gas turbines are typically sold only in combination with a remote diagnostic capability and some type of long-term contract. The level of commitment is defined by the customer according to their service needs.

One turbine specialist's opinion from the turbine user side was that OEMs should offer remote diagnostics inseparable with new machines without specifying a separate price for it. During warranty period the produced reports and services should then be able to indicate enough benefits for the customer to continue the service agreement afterwards. One improvement would be to provide more proactive diagnostics. Warranty periods are short compared to the time it usually takes for the long-term trends to show significant changes and if only these are monitored and reported, the customer might not see enough added value in the diagnostic services. The turbine specialist also criticized the abstractness and expensiveness of current value propositions in diagnostic services, and the long time it takes to build the required setups for remote connections. Nonetheless, the expectation was that the benefits would surely outweigh the costs if only the OEM did not demand too high a price.

New steam turbines are only a small portion of all existing turbines and the quantitative proportion is decreasing. Most of the turbines are long past their warranty periods and first major overhauls as well. Since the different overhauls have been executed by a variety of contractors with varying service quality, other service providers might have difficulties knowing what exactly has been done and how. Different combinations of DCSs and TCSs further complicate the configuration of digital services. There is no license solution for the implementation of diagnostic capabilities in the multitude of tailor-made steam turbines. Due to concerns in stand-alone digitalization projects, the configuration might have to be offered with different cost structure. This could mean for example that the customer would not pay anything for the setup installing but instead for the reports if they meet the preset requirements and are considered to have produced additional business value. It was also reflected that maybe service providers should package their value propositions more. This bundling could enable multiple less valuable digital solutions to become attractive enough for investments. The implementation of long-term programs and service agreements might have the same effect.

Data-driven advanced diagnostic solutions enable OEMs and other service providers to offer long-term service agreements, long-term programs and O&M contracts. Compared to single transaction stand-alone contracts, these service contract types offer more benefits along with extended supplier responsibility, O&M contracts requiring the most commitment. O&M contracts are implemented predominantly in gas turbines and CCPPs because many purchasers in those industries usually want to be less involved in the operation of the plants. Both utility and industrial steam turbine users have historically wanted and most likely will continue to be strongly involved in most of the processes and operations. Thus, their interest will most likely be in those long-term contracts that would let them focus on their core competences, gain shorter response times and increased availability of special turbine know-how.

Long-term programs and service agreements necessitate better condition monitoring and data sharing but would also facilitate other digitalized asset management solutions such as quick remote services, more synchronized ERP systems and documenting, and life cycle cost optimization. Fixed fees together with long-term certainty could bring partners closer to each other through common interests. For instance, fixed costs that cover major overhauls would incentivize service providers to enhance their maintenance operations but at the same time availability guarantees would necessitate high quality operations. This would reduce the risk for erroneous refurbishments and assembly. The level and effectiveness of different guarantees could be improved with higher fixed fees. Undoubtedly, this arrangement could be especially profitable for turbine operating companies if the diagnostic service can justify fewer major overhauls during the long-term contract.

If the revenue model in long-term contracts is based on for instance fixed monthly fees, the turbine user might end up paying less than in short-term contracts. This could be partly due to the “base load” for service demand which might allow service provider to reduce prices. The implementation of digital remote consulting and fact-finding capabilities might have similar cost reduction effect due to more efficient utilization of service provider’s field service resources. Fixed fees would also reduce the risk of supplier charging excessively of their services in cases where the turbine customer is forced by the circumstances to use them. Other alternative is that the turbine user ends up paying the same in the long run but receives higher quality of service. Continuous partnerships would facilitate fast response times, reduce the risk of incorrect operation, and let customers have more influence on the solutions they implement. Long-term programs and service agreements are not possible without better diagnostic capabilities, because otherwise the risks for the service provider would not remain in reasonable level.

When coupled with the long-term service agreement or programs the remote diagnostic capabilities could offer a lot more benefits in contrast to stand-alone services and have a much lower threshold to be used than currently. This view was shared by many interviewees on both purchaser and contractor side. The combination might enable completely new ways and models of co-operation and consultation and increase revenue streams from existing value propositions for both parties. Better availability and performance guarantees are some plausible examples. It would also enable big opportunities with cost reductions in different section of the digitalized asset management. Examples include optimally focused maintenance works and fewer spare parts changed just in case. These would also apply in a smaller scale to stand-alone services, but partnership business models facilitate mutual benefits better. For example, when a diagnostic service provider is responsible for the maintenance as well, it is easier to properly incentivize improvements in procedures. This is because long-term service contracts change the value creation and delivery systems. The change also supports the implementation of best practices.

Scaling up the benefits of digitalized asset management systems would necessitate steam turbine operating companies to allow a lot more data collection. Many interviewed turbine end users recognized this conditionality and were somewhat consenting to the change of mindset as long as the rules and limits of data sharing and utilization are made unmistakably clear. Longer partnerships can enable more open data collection and sharing and mutually beneficial solutions without risking the competitiveness of either party. The increased depth of data use can open big opportunities in advanced diagnostics. Figure 10 demonstrates some prospective business value that could be derived in the future.

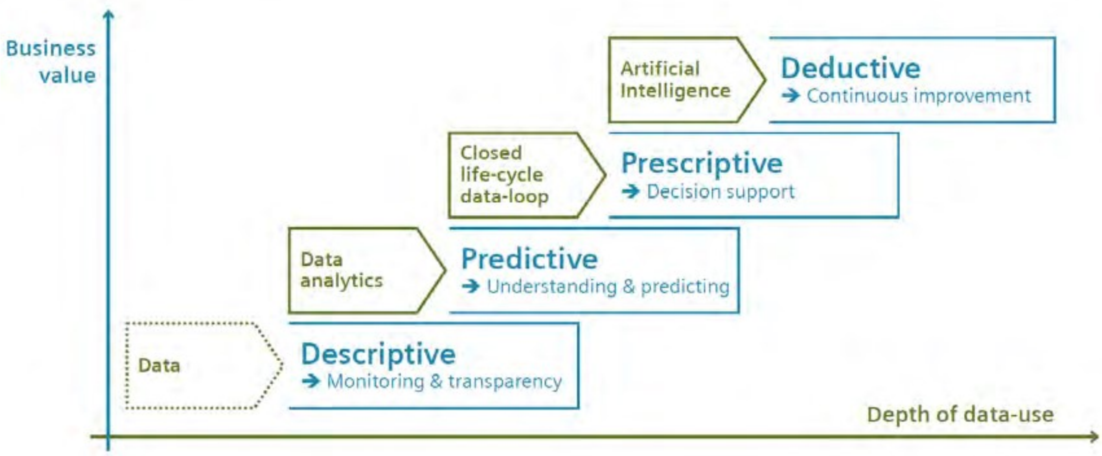

Figure 10. Increased business value of diagnostic services derived from deeper data use. (Siemens 2017)

Together with advanced remote diagnostic capabilities the long-term contracts also allow service provider to substitute customer's unavailable core resources and competences. AR and shared view could for example facilitate remote consulting and guidance that would be done in collaboration with customer's own or local third-party field service organizations. The added visualization of these solutions could enable high quality service even when the field personnel had less domain know-how. This would also increase the performance of OEM's perhaps otherwise insufficient local service organization.

Harmonization of value capture models through long-term programs and service agreements can strengthen the relationship and trust between parties. Other effect would be for example that the reduced need for asset management services due to better solutions developed by the OEM would not reduce its own profitability. Some experiences about the benefits of long-term services can be observed in gas turbine industry, which has used that business model for a long time. One remarkable difference compared to current steam turbine service industry is the "base load" for service demand. This has alleviated pressures to downshift service organizations and reduced the overall risks for both parties.

The mutual understanding, that long-term contracts together with remote diagnostics have the possibility to be more beneficial compared to the current business model and stand-alone connections, raises the question why long-term programs and service agreements are not implemented more often in steam turbine asset management. One factor is the contractor's ability to demonstrate the advantages of long-term services to a less specialized purchaser. Also, the contractor's capability to meet the resulting service demand and requirements must be considered. In regard to the former, a notion from the customer side was that the supplier might need to communicate future maintenance cost better. Many customers lack the know-how to forecast the turbine-related life cycle costs. When for example upcoming overhaul costs are factored into a long-term contract and distributed over the years, it can seem more expensive than a separately acquired maintenance far in the future.

Some turbine customers especially on the industrial side have become accustomed to steam turbines being reliable and durable, requiring little maintenance and almost no attention during operation. Therefore, it seems to be challenging to argue for more continuous condition monitoring. Customers may not value operational services enough. If the operating companies had more realistic perspective about life cycle maintenance demands, possible costs and the risks of production losses they might better understand the benefits of a long-term service relationships. Steam turbine overhaul intervals are so long that operating companies have challenges keeping the sufficient know-how required in their purchasing organizations. It is neither profitable to keep the know-how completely in-house nor easy to find the skillful workforce to the task. Long-term service contracts could alleviate this problem by enabling the transferring of some responsibilities to a partner organization.

The increasing customer's dependency in long-term contracts should be compensated with significant additional value, enough guarantees and a possibility to termination for convenience. Otherwise customers might see it as too great a threat to be tied to a single service provider. This additional value that is tied to long-term service agreements and programs should be demonstrated and specified very carefully and transparently. Currently costs and added value were considered to be imbalanced or not fully known. In order to make the attitude change happen from preferring short-term contracts to considering long-term contracts more advantageous, service providers should give much more attention to value they can offer during the life cycle of a turbine.

There is a clear trend to put more emphasis on the aftersales services. It seems that nearly all other digitalized asset management solutions for steam turbines would be one way or the other based on better remote diagnostic capabilities. Therefore, the implementation of these systems should be in the primary focus of both service providers’ and customers’ approaches. The maximum potential of digitalized asset management services and solutions can be unlocked with long-term partnerships, because they enable less risky business models that are necessitated for deeper and more open data utilization and sharing. Manufacturing business of those OEMs that are engaged also in aftersales services might end up with smaller profits. Increased and continuous service demand would however compensate smaller revenue from spare part sales.

More focus in aftersales services would most likely bring big competitive advantages for those turbine operating companies who are falling short of steam turbine-related competence. Advanced services necessitate more open data exchange which necessitates for example investments to remote connections. Demands for short payback periods might have to be eased in first minimum data connections so that possibilities of digitalization can be better experimented with. If experimental projects are not allowed, the progress will fall farther behind other more profitable industries with more mature digital solutions.

It appears that the information about novel digitalized solutions does not shift optimally between different section inside and between organizations. This implies that opportunities should be communicated better. Customers cannot demand specific improvements if they are not aware that solutions exist. Service provider is unable to offer best solutions and practices if the sales organization does not interact with the research and development departments or for example with their own diagnostic specialists. The more profound domain know-how of OEMs and some service providers indicates that the initiative is with them.

5 Conclusion

The discussions with the interviewees revealed many practical and technical challenges that are met throughout the asset management of steam turbines. Challenges in condition monitoring included turbine operating companies' lack of steam turbine-related know-how and the lack of advanced diagnostic features in condition monitoring systems. Data was observed to not be used optimally. Alarm systems are in need of improvements that could reduce the risk of erroneous operations. Challenges in maintenance include unforeseen findings that prolong major overhauls. Erroneous, slow and outdated reports were a reoccurring problem. Documenting systems lack connectivity, centralization and user-friendliness. Supply chains were considered slow and somewhat unreliable. Challenges in fleet management include lack of resources and skilful workforce. Life cycle assessment of different operations, investments and procedures was considered to be hard. Lack of systems that would facilitate steam turbine fleet management and better planning was observed.

Interviewees on both purchaser and service provider sides observed multiple opportunities with the digitalization of asset management systems and procedures. These opportunities could benefit both sides and most of them would apply to utility and industrial steam turbines alike. Opportunities of digital solutions in condition monitoring include better connection of measured data and reports and control room diaries. User-friendly interfaces and more illustrative presentation of data were hoped for. These could be facilitated with the implementation of digital twin capabilities. Alarm filtering, predictive anomaly detection with AI, and remote consulting in anomaly situation were seen possibly very beneficial. Also, suggestion for operational parameters and predictions for future maintenance needs were desired.

Opportunities of digital solutions in maintenance include real-time editing and good connectivity of documents, reports and all other data, including supply chain information. Digital twin capabilities in maintenance systems would be very beneficial. If utilized properly, they could also enable insightful analytics that would work as a basis for better decision making. Remote guidance and fact-finding were seen desirable. Additive manufacturing could enhance mobility and agility of maintenance procedures. Opportunities of digital solutions in fleet management include centralized databases. Better connection of data from different steam turbines could enable problem case referencing with the help of machine learning. AI solutions could work as the basis for criticality and life cycle assessments in ERP systems. Remote diagnostic capabilities might enable outsourcing of those operations that turbine operating companies consider to be out of their core competences.

Technical and practical problems that are hindering the implementation of digitalized asset management solutions for condition monitoring of steam turbines include the difficulty to substitute visual inspection of some critical parts with digital monitoring. Turbine know-how is challenging to turn into algorithms. The complexity of turbine systems hinders better and more intuitive alarm filtering because automatic criticality assessment would be hard to make absolutely reliable. Many condition monitoring systems require a lot of additional configuration works that can increase the cost of these solutions and thus make them undesirable for purchasers.

Costs of advanced diagnostics are not in balance with the perceived additional value due to scarcity of clearly demonstrated business cases. Diagnostic services have been offered mostly in combination with long-term contracts without properly addressing the issues with increased commitment. Stand-alone connections then again are hard to make profitable. Their benefits are difficult to demonstrate for example due to slowness of occurring changes and the short time allowed to the demonstration. OEMs would be most capable of developing advanced diagnostics, but in the current business model they lack strong financial incentives to it. Case-by-case acquisitions, short-term contracts and lack of focus to aftersales services hinder the diagnostic service providers' ability to remain competitive.

Implementation of digitalized asset management solutions for maintenance is hindered by for instance strong know-how protection to maintain OEM's bargaining power. Also, the lack of financial incentives for the OEM to develop services and solutions that would speed-up overhauls is evident. Stand-alone connections for remote fact-finding are not considered beneficial enough compared to data security risks and setup costs. Based on inadequate life cycle cost and opportunity cost assessments, short-term service agreements are believed to be cheaper than long-term contracts. Insufficient emphasis is given to O&M services and needs in the purchasing processes. This hinders the implementation of digital twin capabilities that would facilitate plant and turbine usability and efficient maintenance.

Problems that are hindering the implementation of digitalized asset management solutions for fleet management include the customizable nature of steam turbines. Problem case referencing is challenging to develop because turbines and cases are so diverse. Complexity of data collection and reluctance to more open data exchange between service provider, customer and third-party systems make fleet management challenging. Increased sharing of know-how in the current business model could compromise OEM's competitiveness. Turbine operating companies desire leaner own resources, but short-term contracts hinder service providers from employing sufficient and quickly available aftersales service organizations. These would allow turbine end users to outsource more those operations that are not in their core competences, but without the base load for work demand service providers cannot meet customer needs.

Successful digital strategy necessitates carrying out improvements that steam turbine operating companies consider valuable. Improvements and service concepts that reflect customer needs and concerns include building a quickly available steam turbine specialist organization with remote access and diagnostic capabilities. Human guidance is preferred to automatic analytic tools. Remote diagnostic service organizations should include better combination of automation system and turbine expertise. Sufficiently large field service organization with fast response time was observed uniformly to be in the best interest of steam turbine operating companies. Good reliability of operations and predictability of costs are highly valued as well. Focus to maintaining and providing these should be strengthened.

In order to implement digitalized asset management for steam turbines the strategy needs to address perceived concerns in the business, such as the lack of long-term perseverance and consistent reporting in digitalization projects. Vaguely delegated responsibilities and overlapping use of limited resources in long projects should be avoided. If longer intervals between overhauls are to be pursued, the optimization of maintenance duration in major overhauls should be focused on. This will require better predictive assessment of upcoming maintenance needs. Demonstrating other less evident additional value in digitalized asset management services and systems could be facilitated with the better involvement of diagnostic specialists into tendering processes. Customers should better include life cycle costs as part of their evaluation criteria in purchases. OEMs might have to make a decision in principle to start providing aftersales services, such as remote diagnostics as an integral part of their steam turbines, similar to gas turbines. Services should also be more proactive and designed so that the customer would not need a separate turbine specialist to comprehend provided contents.

Implementation of different business models would facilitate the utilization of best practices and the most beneficial digital solutions, and help meeting the needs of steam turbine operating companies. Remote diagnostic services enable suppliers to offer long-term contracts and extend their responsibilities. These partnership business models facilitate mutual benefits better than competition with short-term service agreements. They lower the business risk for all parties and incentivize effective and higher quality of services. Collaborative and interactive long-term partnerships also alleviate turbine operating companies' lack of turbine know-how and other key resources. By allowing parties to focus on their core competences and by establishing a base load of services, long-term contracts can increase performance without compromising competitiveness.

Overcoming the challenges of digitalization and hindrances to long-term partnership business models necessitates inclusive discussion about the limits and rules of data use. Costs and added value of digitalized asset management solutions are still considered to be imbalanced or not fully known. Thus, a more transparent comparison about the life cycle costs, maintenance needs and implementable solutions and services in different business models would be beneficial.

References

Arnold, C. & Kiel, D. 2016. *How Industry 4.0 changes business models in different manufacturing industries.* ResearchGate [pdf] Available at: https://www.researchgate.net /publication/304494710 [Accessed 8 Jan. 2019]

AWS. 2018. *Types of Cloud Computing.* [online] Available at: https://aws.amazon.com/ types-of-cloud-computing/ [Accessed 12 Dec. 2018]

Bocken, N., Short, S., Rana, P. & Evans, S. 2014. *A literature and practice review to develop sustainable business model archetypes.* Journal of Cleaner Production. Vol. 65. pp. 42-56

Borgia, E. 2014. *The internet of things vision: Key features, applications and open issues*. Computer Communications. Vol. 54. pp. 1-31

Borkar, S. & Pande, H. 2016. *Application of 5G next generation network to Internet of Things.* IEEE. ISBN 978-1-5090-0044-9

Chen, C. & Zhang, C. 2014. *Data-intensive applications, challenges, techniques and technologies: A survey on Big Data.* Information Sciences. Vol. 275. pp. 314-347.

Cisco. 2015. *IPv6 for the Enterprise in 2015*. White paper. [pdf] Available at: https://www.cisco.com/ c/en/us/products/collateral/ios-nx-os-software/enterprise-ipv6-solution/whitepaper_c11-586154.pdf [Accessed 7 Dec. 2018]

Díaz, M., Martín, C. & Rubio B. 2016. *State-of-the-art, challenges, and open issues in the integration of Internet of things and cloud computing*. Journal of Network and Computer Applications. Vol. 67. pp. 99-117

Dijkman et al. 2015. *Business models for the Internet of Things*. International Journal of Information Management. Vol. 35:6. pp. 672-678

Drath, R. & Horch, A. 2014. *Industrie 4.0: Hit or Hype?* IEEE Industrial Electronics Magazine. Vol. 8:2. pp. 56-58. ISSN 1941-0115

Emani, C., Cullot, N. & Nicolle, C. 2015 *Understandable Big Data: A survey*. Computer Science Review. Vol. 17. pp. 70-81

Evans, P. & Annunziata, M. 2012. *Industrial Internet: Pushing the Boundaries of Minds and Machines*. General Electric. Available at: https://www.ge.com/docs/chapters/ Industrial_Internet.pdf [Accessed 7 Dec. 2018]

Fitzgerald et al. 2013. *Embracing Digital Technology A New Strategic Imperative*. Research report. MIT Sloan Management Review. Available at: https:// sloanreview.mit.edu/projects/embracing-digital-technology/ [Accessed 7 Feb. 2019]

Fouad, M., Oweis, N., Gaber, T., Ahmed, M. & Snasel, V. 2015. *Data Mining and Fusion Techniques for WSNs as a Source of the Big Data.* Procedia Computer Science. Vol. 65. pp. 778-786

Ge, Z., Song, Z., Ding, S. & Huang, B. 2017. *Data Mining and Analytics in the Process Industry: The Role of Machine Learning*. IEEE. Vol. 5. pp. 20590-20616. ISSN 2169-3536

Géczy, P., Izumi, N. & Hasida, K. 2012. *Cloudsourcing: Managing Cloud Adoption*. Global Journal of Business Research. Vol. 6:2. pp. 57-70.

Goodfellow, I., Bengio, Y. & Courville, A. 2016. *Deep Learning*. MIT Press. 781 p. Available at: http://www.deeplearningbook.org/ [Accessed 4 Jan. 2019]

Hakala. M, 2017. The business models of internet of things application enablement platforms. Master's Thesis. Aalto university, School of Business. Espoo. 85 p.

Höller et al. 2014. *From machine-to-machine to the Internet of things: Introduction to a new age of intelligence*. Academic Press. 352 p. ISBN 978-0-12-407684-6

IBM. 2018. *Defining IaaS, PaaS and SaaS*. [online] Available at: https://www.ibm.com/cloud/learn/iaas-paas-saas [Accessed 12 Dec. 2018]

IIC. 2017. *The Industrial Internet of Things Volume G1: Reference Architecture*. Industrial Internet Consortium. Available at: https://www.iiconsortium.org/IIC_PUB_G1_V1.80_2017-01-31.pdf [Accessed 7 Dec. 2018]

ITU. 2018a. *Setting the Scene for 5G: Opportunities & Challenges*. [pdf] ISBN 978-92-61-27591-4

ITU. 2018b. *Assessing the Economic Impact of Artificial Intelligence.* Issue Paper No.1. Available at: https://www.itu.int/dms_pub/itu-s/opb/gen/S-GEN-ISSUEPAPER-2018-1-PDF-E.pdf [Accessed 20 Dec 2018]

ITU-T. 2012 *Recommendation Y.2060: Overview of the Internet of things*. Available at: https://www.itu.int/rec/T-REC-Y.2060-201206-I [Accessed 7 Dec. 2018]

Kauppinen, J. 2018. *Turbiinitekniikka. 1st ed.* Tampere, Finland: Tammertekniikka. 321 p. ISBN-13: 978-952-5491-92-0

Laney, D. 2001. *3D data management: Controlling data volume, velocity and variety*. META Group Inc. Available at: https://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf [Accessed 19 Dec. 2018]

LeCun, Y., Bengio, Y. & Hinton, G. 2015. *Deep Learning.* Nature. Vol. 521. pp. 436-444

Li, Y. 2018. *Deep Reinforcement Learning: An Overview.* Cornell University. arXiv:1701.07274 [Accessed 2 Jan. 2019]

Manyika et al. 2011. *Big data: The next frontier for innovation, competition, and productivity*. McKinsey Global Institute. Available at: https://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/big-data-the-next-frontier-for-innovation [Accessed 20 Dec. 2018]

Manyika et al. 2015. *The Internet of Things: Mapping the value beyond the hype*. McKinsey Global Institute. Available at: https://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world [Accessed 8 Jan. 2019]

Mell, P. & Grance, T. 2011. *The NIST Definition of Cloud Computing*. [pdf] Available at: https://doi.org/10.6028/NIST.SP.800-145 [Accessed 11 Dec. 2018]

Miller, D. 2018. *Blockchain and the Internet of Things in the Industrial Sector*. IT Professional. Vol. 20:3. pp. 15-18. IEEE. ISSN 1941-045X

Minoli, D. & Occhiogrosso, B. 2018. *Blockchain mechanisms for IoT security.* Internet of Things. Vol. 1-2. pp. 1-13

Miraz et al. 2015. *A review on Internet of Things, Internet of Everything and Internet of Nano Things*. IEEE. ISBN 978-1-4673-9557-1

Mnih et al. 2015. Human-level control through deep reinforcement learning. Nature. Vol. 518. pp. 529-533

Nilsson, N. 2009. *The Quest for Artificial Intelligence*. Cambridge University Press. 580 p. ISBN 9780521122931

Osterwalder, A., Pigneur, Y. & Clark, T. 2010. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers.* John Wiley & Sons, Inc. 278 p. ISBN 978-0-470-90103-8

Osterwalder, A., Pigneur, Y. & Tucci, C. 2005. *Clarifying business models: origins, present, and future of the concept.* Communications of the Association for Information Systems. Vol. 16. pp. 1-25

Porter, M. & Heppelmann, J. 2014. *How smart, connected products are transforming competition*. Harvard Business Review Vol. 92:11 64-88

PwC. 2017. *Sizing the price: What's the real value of AI for your business and how can you capitalise?* [pdf] Available at: https://www.pwc.com/gx/en/issues/analytics/assets/pwc-ai-analysis-sizing-the-prize-report.pdf [Accessed 20 Dec. 2018]

Richardson, J. 2008. *The business model: an integrative framework for strategy execution.* Strategic Change. Vol. 17. pp. 133-144

Ruohola, K. 2014. *Höyryturbiinin revisiovälin pituuden vaikutus revision kestoon ja havaittuihin vaurioihin.* Diplomityö. Aalto-yliopisto, Koneenrakennustekniikan laitos. Espoo. 82 p.

SFS-EN 13306. 2017. *Maintenance. Maintenance terminology*. Helsinki: Finnish Standards Association. 93 p.

SFS-EN 16646. 2014. *Maintenance. Maintenance within physical asset management*. Helsinki: Finnish Standards Association. 35 p.

SFS-ISO 55000. 2014. *Asset management. Overview, principles and terminology*. Helsinki: Finnish Standards Association. 19 p.

Siemens. 2017. *MindSphere. A white paper issued by Siemens PLM Software*. [pdf] Available at: http://www.siemens.com.tw/release/pdf/MindSphere_Whitepaper_EN.pdf [Accessed 5 Feb 2019]

Stock, T., Obenaus, M., Kunz, S. & Kohl, H. 2018. *Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential*. Process Safety and Environmental Protection. Vol.118. pp. 254-267

Uckelmann, D., Harrison, M. & Michahelles, F. 2011. *Architecting the Internet of Things.* Springer. Berlin Heidelberg. 378 p. ISBN 978-3-642-19157-2

Vitie, T. 2017. *Digitalisaation mahdollisuudet energiantuotannossa ja jakelussa.* Diplomityö. Tampereen teknillinen yliopisto. Tampere. 44 p.

White, M. 2012. *Digital workplaces: Vision and reality.* Business Information Review. Vol. 29:4. pp. 205-214

Zeng, M. 2018. *Alibaba and the Future of Business*. Harvard Business Review. Vol. 96:5. pp. 88-96

Ziegler, S., Crettaz, C. & Thomas, I. 2014. *IPv6 as a Global Addressing Scheme and Integrator for the Internet of Things and the Cloud.* IEEE. ISBN 978-1-4799-2653-4

Interviews

Beer, W. 2019. Doctor. Head of Remote Diagnostics. Siemens AG. *Interview.* 28.5.2019.

Etelämäki, M. 2019. Risk Engineer, Power Industry Specialist. If Vahinkovakuutus Oyj. *Interview.* 16.4.2019.

Helin, A. 2019. Managing Director. Power CS Oy. *Interview.* 4.4.2019.

Korhonen, M. 2019. Control room Engineer. Vapo Oy. *Interview.* 3.4.2019.

Kotilainen, J. 2019. Project Manager, Operative Investments. Metsä Fibre Oy. *Interview.* 5.4.2019 and 15.4.2019.

Lindblad, P. 2019. Maintenance Manager. Helen Oy. *Interview.* 4.3.2019.

Parviainen, P. 2019. Turbine Specialist. Vantaan Energia Oy. *Interview.* 15.2.2019.

Tervo, J. 2019. Manager, Nuclear Power and Production Development. Pohjolan Voima Oyj. *Interview.* 10.4.2019.

Varmavuo, J. 2019. Senior Specialist. Varmavuo Oy. *Interview.* 4.6.2019.