TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
2/2019

Reliability Management Approach for a Virtual Enterprise of SMEs in a Manufacturing Domain

KASHIF MAHMOOD

TTÜ PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Mechanical and Industrial Engineering
This dissertation was accepted for the defence of the degree 10/12/2018

Supervisor: Assoc. Prof. Eduard Ševtšenko
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor: Prof. Tauno Otto
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Opponents: Prof. Marcello Urgo
Department of Mechanical Engineering
Polytechnic University of Milan
Milan, Italy

PhD Researcher, Tõnu Leemet
Institute of Technology
Estonian University of Life Sciences
Tartu, Estonia

Defense of the thesis: 15/01/2019, Tallinn

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been previously submitted for doctoral or equivalent academic degree.

Kashif Mahmood

----
signature

European Union
European Social Fund
Investing in your future

ISSN 2585-6898 (publication)
ISBN 978-9949-83-380-1 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9949-83-381-8 (PDF)

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
2/2019

Usaldusväärsuse juhtimise raamistik tootmisvaldkonna väikese ja keskmise suurusega virtuaalettevõtetele

KASHIF MAHMOOD

TTÜ KIRJASTUS

Preface

I have started my doctoral studies (production engineering as a major) in the year of 2014 in the Department of Mechanical and Industrial engineering at Tallinn University of Technology. Since my background was related to the field of industrial and manufacturing engineering, and I did MSc in industrial engineering and management from TalTech as well. Moreover, during my master studies I spent two semester in Linköping University, Sweden for exchanges studies and wrote my master thesis there on the topic of *Lean approach in manufacturing and service sectors*. Later, I found myself to be motivated and interested in the areas of manufacturing systems analysis and simulation, process improvement and management. Therefore, I continued the research in the similar field, meanwhile I got an opportunity to pursue as a PhD student under the supervision of Prof. Tauno Otto and Assoc. Prof. Eduard Ševtšenko. During the doctoral studies, beside of my project *Collaboration enhancing sustainable conceptual model development*, I have worked on couple of industrial projects related to process analysis and improvement, followed by involved in digital manufacturing and industry 4.0 associated projects and academic courses. I have been in Tampere University of Technology, department of Mechanical Engineering and Industrial Systems as a visiting doctoral researcher under the supervision of Prof. Minna Lanz and Assoc. Prof. Andrei Lobov, where I worked on the project of *Real-Time Visualisation of the Status of a Production System and Production Data*. My PhD dissertation is a combination of the projects that I have been involved and worked on. Overall, my doctoral studies journey is full of delightful experiences, and during this tenure I got a chance to meet many professional and academic personnel.

Contents

List of Publications

This dissertation consists of a summary and the following publications, which are referred to in the text by their Roman numerals.

I Mahmood, K.; Shevtshenko, E.; Karaulova, T.; Otto, T. (2018). Risk assessment approach for a virtual enterprise of small and medium-sized enterprises. *Proceedings of the Estonian Academy of Sciences*, 67 (1), 17-27.

II Shevtshenko, E.; Poljantchikov, I.; Mahmood, K.; Kangilaski, T.; Norta, A. (2015). Collaborative Project Management Framework for Partner Network Initiation. *Procedia Engineering*, 100, 159-168. Proceedings of the 25th DAAAM International Symposium on Intelligent Manufacturing and Automation, Elsevier.

III Mahmood, K; Shevtshenko, E. (2015). Analysis of machine production processes by risk assessment approach. *Journal of Machine Engineering*, 15 (1), 112-124.

IV Mahmood, K.; Karaulova, T.; Otto, T.; Shevtshenko, E. (2017). Performance Analysis of a Flexible Manufacturing System (FMS). *Procedia CIRP*, 63, 424-429. Proceedings of the 50th CIRP CMS, Elsevier.

V Mahmood, K.; Lanz, M.; Toivonen, V.; Otto, T. (2018). A Performance Evaluation Concept for Production Systems in an SME Network. *Procedia CIRP*, 72, 603-608. Proceedings of the 51st CIRP CMS, Elsevier.

Publications copies are enclosed in the appendix.

Author’s Contribution

Following are the authors’ contribution to the publications:

For **Article I**, the author designed and conducted the case study, analyzed the results, and performed the whole writing process.

For **Article II**, the author introduced a virtual enterprise model from a collaborative network of SMEs and its project management, and contributed to the writing process.

For **Article III**, the author contributed to the main idea of the paper and developed the risk assessment approach, performed the case study, analyzed the results, and executed the writing process.

For **Article IV**, the author developed the simulation model, the analysis of the results, and contributed in all of the writing process of described models.

For **Article V**, the author performed the concept and schematics development, conducted the case study, and carried out the writing process.

List of Abbreviations

API	Application Programming Interface
BPMN	Business Process Modelling Notations
CIRP	The International Academy for Production Engineering
CN	Collaborative Network
CPPS	Cyber Physical Production System
CPS	Cyber Physical System
ERP	Enterprise Resource Planning
EPC	Event-driven Process Chain
FTA	Fault Tree Analysis
IIoT	Industrial Internet of Things
IT	Information Technology
IRM	Institute of Risk Management
IDEF	Integrated Definition
ISO	International Organization for Standardization
IoT	Internet of Things
JIT	Just-in-time
KPIs	Key Performance Indicators
OE	Operational Excellence
OEE	Overall Equipment Effectiveness
PN	Partner Network
PE	Performance Evaluation
PMBOK	Project Management Body of Knowledge
PS	Production Systems
RM	Reliability Management
RA	Risk Assessment
SMEs	Small and Medium-sized Enterprises
SRA	Society for Risk Analysis
SCOR	Supply Chain Operations Reference
SPN	Sustainable Partner Network
NIST	National Institute of Standards and Technology
TPS	Toyota Production System
TPM	Total Productive Maintenance
VAC	Value Added Chain
VA	Value Chain
VE	Virtual Enterprise
VSM	Value Stream Mapping

1. Introduction

The introduction comprises of background and research gaps of the study, followed by research problems and framework description. Objectives and research questions are also described in this section. Moreover, research process and structure of the dissertation are included as well.

1.1 Background and Research Gaps

In recent times, the rapid evolvement of technologies, as complexity has increased in the manufacturing of products, and companies are more dedicated in their particular fields. These changes brought a greater impact on small and medium-sized enterprises (SMEs). Therefore, it is difficult to possess all the necessary technologies and expertise in one house. Due to these challenges faced by manufacturing enterprises, they are continuously seeking collaboration with other enterprises and form a network.

The network can be presented as a Sustainable Partner Network (SPN) [1] and work as a Virtual Enterprise (VE) to fulfill business opportunity and having identical goals. Thus, SMEs can stay competitive in the global market and able to compete with larger firms. Because those larger firms are so influential and effective to have a dominance even in national administrations or government [2], [3] & [4]. They have a monopoly in particular markets, which may affect competitiveness or lead to economic crises or a state's economic immobility in global terms. According to the European Commission (Eurostat), SMEs are the main pillar of the European economy and a potential source of economic growth [5]. Therefore, it is needed to build a collaborative environment in the form of SPN of SMEs, where SMEs share their resources to accomplish a common goal. It is not only allowing them to compete with bigger corporations but also provide a fast track to respond to the business opportunity, furthermore, such networks basis to the emergence of a virtual enterprise. Nevertheless, as compared to the traditional enterprise a virtual enterprise is exposed to more complicated risk management issues. For the desired profit and particular goal, a VE has to avoid risks successfully.

Research gap 1: There is a need for studies, how to evaluate the effectiveness of a virtual enterprise, especially the performance of production systems and resources the SMEs possess. If the efficiency of a production system cannot be assessed, then it cannot be properly controlled. This leads to waste of time, money, energy and overloaded staff.

Similarly, in the recent years due to the emergence of new technologies in a manufacturing domain such as Industrial Internet of Things, etc. enabled small enterprises to take advantage of new business models that were not available in the past due to the lack of technology. For this purpose, new technologies are required to meet the basic needs to support SMEs for the implementation of a collaborative network in terms of manufacturing processes and logistics assets. In particular, SMEs need to get insight about the ongoing activities at the factory floor where production systems are located. To achieve real-time production systems monitoring, Internet of Things (IoT) technologies can be employed by SMEs to collect data from the factory floor to enable them to understand the production planning and control activities. The key motivation behind the utilization of such technologies for SMEs is to increase the reliability and productivity of manufacturing processes.

Research gap 2: There is a need for laboratory studies on performance effects of digitalisation practices in the manufacturing and learning on production systems that are similar to those systems in the engineering industry. Evidence on the fundamental effects of digitalisation practices would give insights for industrial managers when making decisions on digitalisation assignments.

1.2 Research Problems and Framework

SMEs involve over 95% of the firms and create an ample share of new jobs in OECD (Organisation for Economic Co-operation and Development) economies with the employment of 60%-70% [6]. SMEs are the main players in the European economy, gear-up economic growth and generate jobs [7] especially in the Nordic countries and Estonia. On the other hand, the advancement in digitalization in those countries, pioneering by Estonia, as there is a trust and consent to adopt the digital services, and implement in all business levels. As a result, virtual enterprise of SMEs can be an appropriate perspective to overcome the lack of skills and competence that an SME fails to establish. The intent of virtual enterprise is to strengthen the competitiveness by providing the features required for SMEs to compete in the market and meet consumer requirements, through shortening the time-to-market of their products and services. The general characteristics of virtual enterprise are [8]:

Business opportunity driven – explore specific business opportunity, networking tendency and temporary.
Bilateral – Sharing core competence among partner SMEs and integration of business processes.
Flexible – SMEs can participate in multiple networks simultaneously, moreover, an SME may enter or leave the network.

However, the reliable and effective working of a VE is still a challenge, and need more attention. Most importantly for the manufacturing SMEs, who are the part of a VE setup, the effective and productive working to the resources such as production systems and their evaluation need to be explored more, since they play a major role to accomplish the goals and for the essence of a virtual enterprise.

The problem is faced by SMEs network or a virtual enterprise; it may lose reliability in terms of time and cost. As a result, VE unable to accomplish a business opportunity. Moreover, there is a lack of expertise to evaluate and visualize the performance of production systems in a SMEs network. Likewise, due to the dynamic manufacturing environment, manufacturing firms may loss process efficiency if the shop floor process cannot be monitored and shared related information on time to the upper level.

1.3 Objectives and Research Questions

The purpose of this thesis research is to develop an approach to assess the risks of a VE and to evaluate the performance of production systems in a VE of SMEs. The main focuses of the work are as follows:

- To provide a concept for analysing the key risk factors and to assess the level of risk a VE faces during its whole functioning period.
- To provide a concept of performance evaluation of production systems in an SME network with the adoption of the Internet of Things (IoT) in manufacturing.

The thesis intends to help decision-makers of a collaborative network of SMEs to formulate and estimate the potential risks and to set up an action plan to mitigate the overall VE risks, which also supports to improve their business model reliability. Moreover, it facilitates how the performance evaluation of production systems should be conducted in a harmonized way and how it may visualize in a network with the help of industrial internet of things. Which leads to enhance the collaboration among SMEs, share their resources and be competitive, hence, capable of earning value from the business opportunity. Therefore, the following research questions (RQ) are taken into account:

RQ1: How to assess the risks in virtual enterprises and to address the risks by the effect of digitalization?
RQ2: How to evaluate the performance of production systems and visualize in SMEs Network based on IoT?
RQ3: What factors are derived, and parameters required to the performance evaluation of production systems?

The research questions are answered stepwise in the five articles.

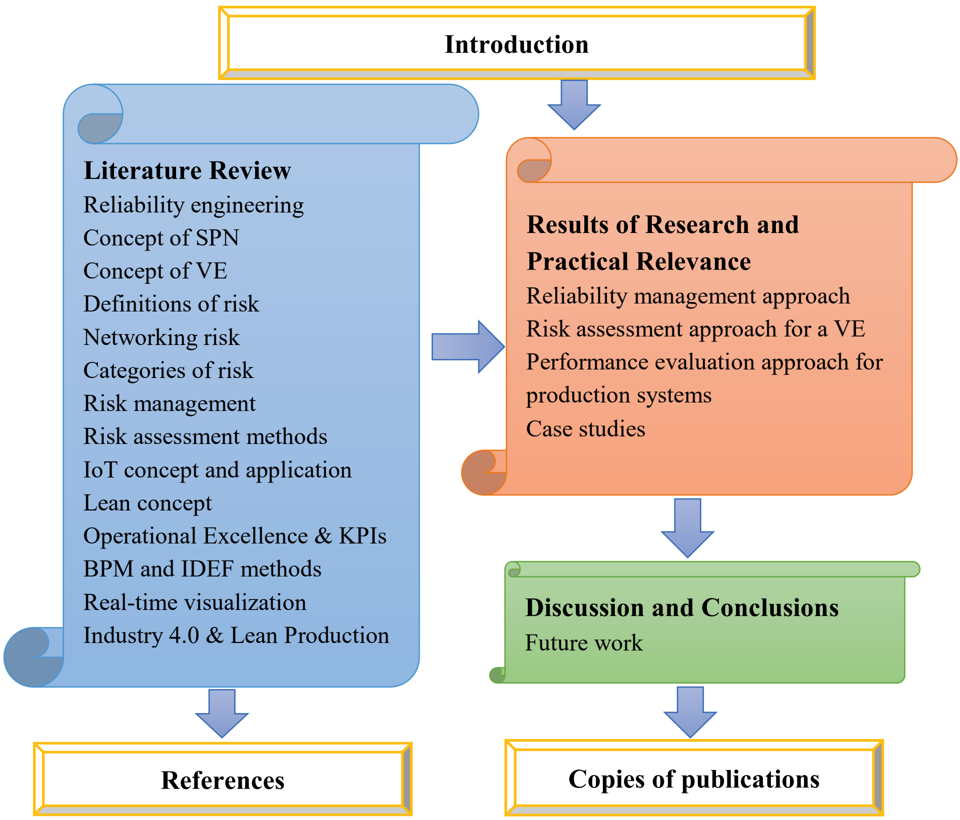
Article I study has responded the RQ1, in this article possible virtual enterprise life cycle risks were identified and assessed.
Article II study has explained the model of a virtual enterprise from a collaborative network, which helped in the interpretation of RQ1.
Article III study has supported to response the RQ1 and RQ2, in the article a risk assessment approach for production systems was developed, which helped for risk evaluation of a virtual enterprise.
Article IV study assisted to answer the RQ2 and RQ3, as the article has described the performance analysis and modelling of production systems.
Article V study has responded the RQ2 and RQ3, in this article performance evaluation concept for production systems in a SMEs network has developed, performance indicators were defined and visualization process was illustrated.

1.4 Research Process and Structure of the Dissertation

This research conveys several methodologies, and it is a combination of different known methods. The project-based risk management and lean performance evaluation of production systems are the key subjects of exploration. Literature review and case studies are the main research techniques. The development of a risk assessment approach includes the methods of process modelling, risk matrix, Fault Tree Analysis (FTA) and the concept of IoT. The developed approach enables to evaluate a VE reliability and facilitates to analyse its vulnerability.

The performance evaluation of production systems approach adopts the methods of business process modelling, KPIs modelling, visual management and the concept of the industrial internet of things (IIoT). The developed approach addresses a harmonized way to evaluate the performance of production systems based on certain Key Performance Indicators (KPIs) and their real-time visualization.

The research study was carried out during 2014 – 2018 at TalTech University. During this period six month from Aug, 2017 to Jan, 2018, the research was conducted in Tampere University of Technology – Department of Mechanical and Industrial Systems. The results of the PhD thesis have been presented at six international conferences. The articles were published in the proceedings of conferences and in the scientific journals. CIRP (The International Academy for Production Engineering), DAAAM (Danube Adria Association for Automation & Manufacturing), Journal of Machine Engineering and Estonian Academy of Science, are the main platforms of publications



2. Literature Review

The literature review comprises of definitions and the brief explanation of different concepts related to the research. This descriptive section helps in the formation of the second chapter, i.e., about the developed concepts and results of the dissertation.

2.1 Reliability Engineering

Recently, organizations have experienced a period of great change in their markets and operations. International and domestic competition is resulting in that many organizations have encountered more and more turbulent and hostile environment. Moreover, the pace of technological change demands the companies to be faster and better; customers have become more appealing. Therefore, competition has become more intense and sophisticated. Good quality performance always a key strategic factor for business success. However, in the current era, it is not only required to compete successfully in the universal market but also keep sustainable is the vital factor in response to these forces.

Thus, the acceptability of a product or service depends on its ability to function satisfactorily over a period of time and this aspect of performance is known as reliability [9]. However, reliability is a wide term and mainly emphases on the ability of an item or a system to perform a required function under specified conditions for a given period of time [10]. Reliability definition is the basis of reliability engineering, as reliability defines the probability of a system to perform its intended function over a particular period under stated conditions. While reliability engineering is a strategic task concerned with predicting and avoiding failures, which is executed throughout the lifecycle of a system or a project, including planning, testing, and operation. Furthermore, risk assessment is a practice that is performed within the concept of reliability engineering. It demonstrates the vulnerability issues of a system, a business project, environment, and machine functioning.

The main purpose of reliability engineering is to evolve the reliability requirements for the system, design the system or product to meet the reliability requirements, form an acceptable reliability program, and implement suitable analysis to monitor the actual reliability of the system or product during its life. Likewise, continuous improvement is a key element of reliability enhancement [11]. It states that an organisation gains from the performance of each step in process cycle. It includes proper work procedure, as well as a complete corrective action platform, supported by a robust root-cause analysis program. The correct application of metrics and/or key performance indicators also plays a crucial role in this element.

Reliability strategies should be the integration of quality, risk, and financial requirements for a enterprise to accomplish the business goals [12]. Additionally, competition, the pressure of schedules and deadlines, the cost of failures, the rapid evolution of new technology, methods and complex systems, the need to reduce product or service costs, and safety considerations all increase the risks of product or service development. These pressures lead to the overall perception of risk. Reliability engineering has developed in response to the need to control the risks [13].

2.1.1 Concept of Sustainable Partner Network and Virtual Enterprise

Initially, the concept of a virtual enterprise was introduced by Byrne, and according to him, the virtual enterprise is “a temporary network of independent companies—suppliers, customers, even erstwhile rivals—linked by information technology to share skills, costs, and access to one another’s markets” [14]. L. M. Camarinha-Matos and H. Afsarmanesh define the VE as “temporary alliance of enterprises that come together to share skills or core competencies and resources to respond more effectively to business opportunities, and whose cooperation is supported by computer networks” [15]. VE consists of a synchronized network of enterprises that perform collectively to deliver a product or service to the end-user [16].

According to Polyantchikov et al. [1] the concept of sustainable partner network evolves from the idea of a partner network, and it is defined as an SME network organisation. SPN is a new organisational structure for an alliance of SMEs, which is a kind of business community composed of organisations that come together in preparation for rapidly responding to business opportunities and worked as a virtual enterprise. SPN is a domain-oriented structure (business area) that consists of standardised business processes. Many SMEs exist in the marketplace, and the idea is to combine their resources to increase capacity. Usually, a SME has limited resources for development, and the SPN environment provides an opportunity to overcome this limitation.

All in all, the descriptions and features from the different points of view presented in the literature, a VE can be described as a new, temporary entity that is created for the fulfilment of a goal and dissolved after the goal is achieved. The Value Chain (VC) or Value Added Chain (VAC) structure of a VE is similar to the structure of a physical enterprise. The further explanation about the concept of VE, collaborative network and partner work are described in the *papers I and II*.

Nevertheless, a VE came across various risk factors. As it is a coalition of enterprises, both internal (within a company) and external uncertainties can exist. The difficulties may contain “*resource unavailability, information flow disruptions within a firm and between enterprises, reduced operational efficiencies, price fluctuations, changes in the political environment, etc., which may lead to potential risks. Risks and opportunities exist side by side in a VE.*” The success of risk management secures an efficient operation not only in the VE but in any organization. Hence, the risk management of the VE now becomes the core topic of attention among SMEs [I].

2.1.2 Risk, Networking Risk and Risk Categories

There are several ways to define a risk, most of them are referred in the *papers I and III*. Risk can be defined as a combination of impact and the likelihood of a potential event (Risk = Impact x Probability). The event might be realized as a failure, a hazard or an opportunity. A comprehensive definition of risk refers as – The ability of an event to impact the effectiveness and efficiency of the core processes of an organisation [17]. Some key definitions of risk are presented in table 1.1.

Table 1.1 Key definitions of risk

Sources	Definition of risk
ISO guide 73 **ISO 31000**	Risk is regularly defined by an event, a change in conditions or consequences. It's an effect of uncertainty on objectives. An effect may be positive, negative, or a deviation from the expected [18].
Institute of Risk Management (IRM)	Risk is the combination of the probability of an event and its consequence. Consequences can range from positive to negative [19].
Society for Risk Analysis (SRA)	It is an uncertainty of outcome, within a range of exposure, ascending from a combination of the impact and probability of potential events [20].
Institute of Internal Auditors	The uncertainty of an event is happening that could have an impact on the achievement of the objectives. The risk is measured regarding consequences and likelihood [21].

Although networking has several benefits, on the other hand it cannot be considered risk free, the same is applied to the VE. The benefits and reasons for networking along with risk factors are described in the *paper I*. Some of the networking risks can be characterised as follows:

- Interdependence – lack of trust, insufficient information sharing
- Quality and capacity constraints of individual enterprises
- Factors such as disruption and delays in deliverables
- Variations in procurement, receivables, inventories, capacity, forecasts and intellectual property

Hopkins [17] describes the division of risk into four categories that are:

- *People* – Lack of right competence, absence and insufficient personnel
- *Premises* – Insufficient or inadequate access
- *Processes* – Lack of information flow and communication among the process owners (nonconformity in transport, production, etc.)
- *Product* – Late and poor product

Those categories defined and referred in the *paper III*. *Paper III* also defines the kinds of risk which are related to the *operator (user), software application* and *system/component*. They were used in the risk assessment of automated production machines.

2.1.3 Risk Management

The brief description of risk management is provided in the *paper I and III*. From the different kinds of literature, risk management considers as the set of actions within an enterprise or organization carry out to deliver the most constructive outcome and reduce the instability or variability of that outcome. Table 1.2 illustrates a few other definitions of risk management. Steps of risk management are depicted in Fig. 1.1, the risk management is an overall process of risk assessment that includes *risk identification*, *risk analysis* and *risk evaluation*. Followed by risk treatment which involves the mitigation of risks. As it is a continuous process, connected by monitoring and review activity to form a close loop to the starting activity, where the background to carrying out risk assessment should be established. Communication and consultation as a supporting activity should work parallel during the whole process cycle.

Table 1.2 Definitions of Risk Management

Sources	Definitions of risk management
ISO guide 73 **ISO 31000**	Integrate activities to guide and control an organisation concerning risk [18]
Institute of Risk Management (IRM)	The process that aims to assist organisations to recognise, evaluate and take action on all their risks in order to increase the probability of success and to reduce the likelihood of failure [19].
PMBOK	It enables the successful analysis and management of the risk associated with a project, risk that could cause the doubt about the ability to deliver a project on time, within budget and desire quality [22].

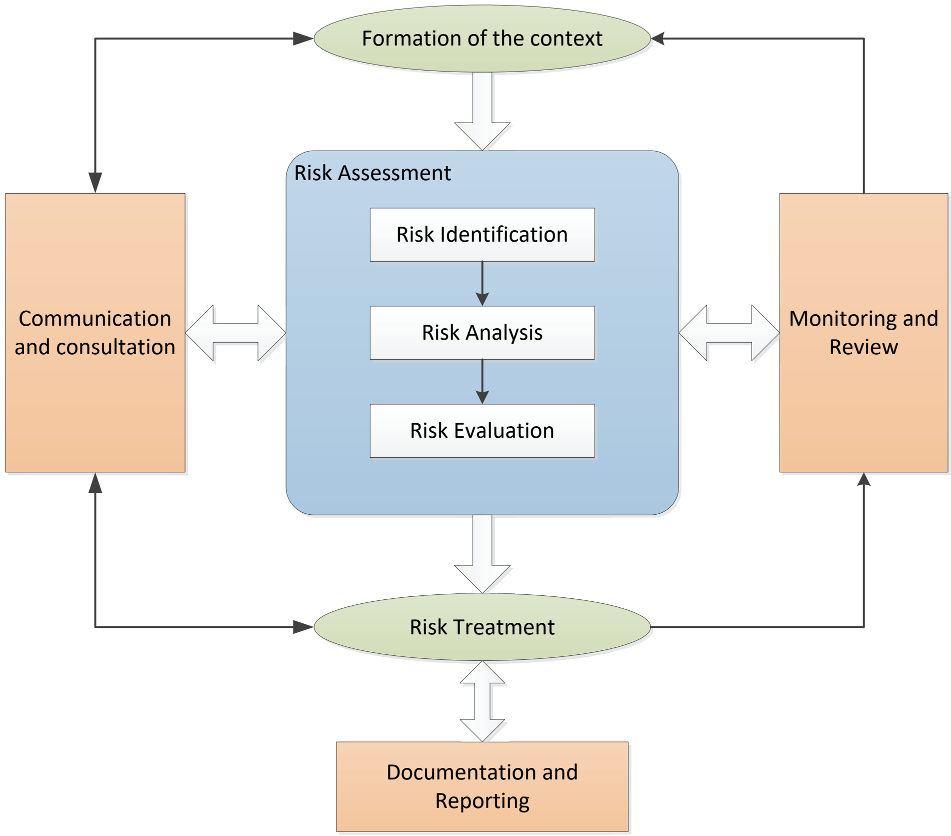


Figure 1.1 The generic risk management process for projects [17], [18], [22]

2.1.4 Risk Assessment Methods

Risk assessment is a technique to identifying and evaluate risks; it is a tool which is presented in the *paper III*, especially for manufacturing process risk assessment. It facilitates to determine and assess the risk. *The paper I and III* provide the details of risk assessment methods which are categorised as *Quantitative*, *Qualitative* and *Semi-quantitative*.

Risk matrix – It is used for the rating of risks after identification. There are several ways to construct a risk matrix for risk evaluation; in the literature authors described the risk matrix differently according to the specific needs. The most common practice is one that determines the relationship between the likelihood of the risk be happening, and the impact of the risk materialise event. Moreover, risk likelihood and impact definitions should be demonstrated in order to rate the risk; it is usually based on a scale either 1 to 10 or high, medium and low. An example of likelihood and impact scales along with risk matrix is established and defined in the *paper III*. The risk matrix might be used to record the outcome of the risk rating exercise and provides a simple visual presentation of the significant risks that have been recognised or identified [17], [23].

Semi-quantitative risk assessment – Semi-quantitative methods used to define the relative risk scale. Such as risk can be classified as "high", "medium" and "low". A number of risk levels may vary from 1 to 10 or more. In a semi-quantitative approach, various scales are considered to illustrate the likelihood of adverse events and their consequences. Analysis of probabilities and their consequences do not require precise mathematical data [24]. The objective is to develop a hierarchy of risks against a quantification, which reflects the order that should be reviewed, mitigate & monitor.

Fault Tree Analysis (FTA) – FTA is a graphical method used in the capacity of risk and reliability analysis. It describes the combinations of events leading to a defined system failure. The system failure mode is represented as the top-event under the fault tree vocabulary. The fault tree includes three logical possibilities and two key symbols. It involves gates in a way that the inputs under the gates signify failures. Outputs at the top of the gates denote a propagation of failure depending on the nature of the logic gates. The three types are as follows [23], [25], [26].

- OR gate – any input causes the output to happen.
- AND gate – all inputs need to occur for the output to occur
- Voted gate – similar to AND gate, but two or more inputs are needed for the output to occur.

According to the axioms of FTA, the likelihood of a high-level event can be defined as:

AND events: $P(A \cap B) = P(A) \times P(B)$

OR events: $P(A \cup B) = P(A) + P(B)$

2.2 Lean Concept

There is no final all-in-one approach to process improvement. Progress depends on managing all components of the value chain to include customer, partners, and suppliers. Lean methodology is considered to accommodate global challenges, and international constraints by eliminating mistakes and reducing waste within existing processes. Lean thinking is intended to make the process better, faster, and more cost-effective [27].

"Lean approach is widely used to eliminate wastes from the systems both in manufacturing and service areas; the lean concept is well-known for its profound improvements, and on the other hand, it is not easy to implement" [28]. However, "*to achieve impressive results in cost, quality and time, lean principles and tools need to be applied to enhance the process performance*" [27]. These principles are enabling a company to differentiate value from waste and facilitate to maximise customer value while minimising waste. Lean approach together with other concepts such as Agile, Resilient and Green are essential in modern business environments to stay competitive and for the effectiveness of collaborative network performance [28].

In the context of process management lean concept facilitates to specify a value, line up value-creating actions in the best sequence, conduct the activities without interruption, and perform them more and more effectively. In short, a lean concept in process management "*provides a way to do more and more with less and less – less human effort, less equipment, less time and less space – while coming closer and closer to*" value-added activities or processes. Lean process management helps organisations to develop their business processes in fewer time and manage them with fewer efforts [29].

Lean Production System – The lean production is a derivative of the Toyota Production System (TPS) which was developed by Toyota Motor Corporation in the last quarter of the 20th century. The TPS incorporates a set of techniques and tools with the management philosophy to entirely eliminate the seven forms of waste (Muda) and to produce profit through cost reduction [30]. The house of TPS is shown in Fig. 1.2, which represents the Lean Production tools and principles, it consists of a roof, two main pillars and foundation element (basement). The triangular roof emphasises the customer-oriented KPIs that focuses on quality, cost and lead time [31], [32]. Continuous improvement of production is the main idea which is the integration of the following tools and principles:

- JIT - Linking production rate to customer demand
- Jidoka - the principle of stopping a process immediately an abnormality occurs
- Andon - the way to signalise problems in the production, "asking help"
- Poka Yoke - Learning by systematic trialling and making a mistake
- 5S - Sort/Set in order/Shine/Standardise/Sustain
- TPM – Total Productive Maintenance
- VSM – Value Stream Map
- Kaizen – continuous improvements
- Visual management
- 5 Why's

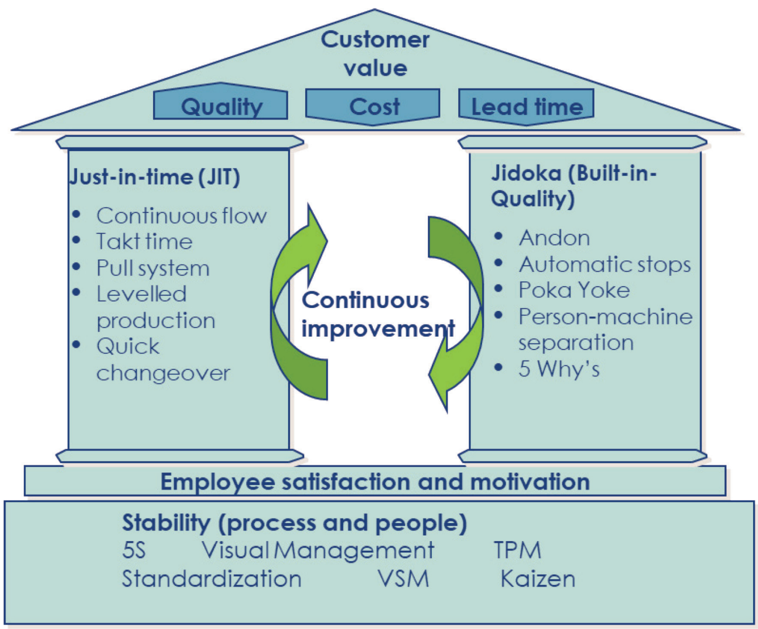


Figure 1.2 House of TPS [31], [32]

Visual management – is an element of a lean approach, helps to improve communication and the response effectively. It is the way to use visual utilities not only to manage the tasks, but also have an eye on schedules, performance tracking, and project status. Moreover, visual supports deliver messages rapidly and develop more interest than the written information. It can display standard versus actual status and broad way of communicating to the audience concisely [33]. Recently, digital visual management gets more attention because of IoT applications, especially in the manufacturing industry to visualise and monitor different performance indicators using real-time digital dashboards.

Value Stream Mapping – is an advanced form of process mapping, which focuses on the process by using the principles of Lean and from the perspective of value. It is the study of specific activities necessary to bring product family from raw material to finished goods as per customer demand that is focusing on information management and physical transformation tasks [34]. It is also known as the heart of lean approach and powerful practice for the visualisation of other concepts like the understanding what the value is and how it can be created by the processes of provision.

2.2.1 Operational Excellence

Operational Excellence (OE) is a comprehensive package of improving and sustaining business performance in which quality management is embedded. It is a similar term as Business Excellence and also includes Manufacturing Excellence and Supply Chain Excellence [35]. Moreover, OE is the way of continuous improvement of the whole sectors of an organisation or a network of SMEs, and it is a lean-driven approach. It is focused on the consistent and reliable execution of business tactic. Likewise, operational performance indicators are necessary to figure out to determine the level of performance of a process or equipment [36].

2.2.2 Performance Analysis of Production Systems

Generally, performance analysis is a primary step in the design process of any system, and it is becoming critically important in order to contribute to effective industrial logistics. Typical production systems related decision problems can be classified as long-term, intermediate-term and short-term. Whereas, the decisions in each term may also be categorised as a long range such as decisions made while designing facilities, shop floor, actual production line, distribution and customer service policy. The intermediate range decisions may include setting up a master production plan, inventory management issues, procurement plan and workforce plan. The short-range decisions usually consist of daily or weekly production schedules, routing issues due to failure and repair management [37].

Furthermore, the impact of a policy decision or a design change on the behaviour of a production system may be measured by observation or estimated using a methodology. This methodology is generally called *performance evaluation* of *production systems*. The concept of 'performance' is self-explanatory, and it is always measured to find out whether a system is doing well or poorly, similarly, better than or worse than a benchmark or a competitor [34]. The requirements of performance evaluation are to come-up with performance criteria which involve a set of measuring parameters, i.e., what to measure, where to measure and how to measure. The ultimate and obvious motivation is to take essential actions to improve the performance of a system.

Paper IV and the introduction of *Paper V* briefly highlights the needs of performance analysis of production systems.

Key performance indicators – KPIs consist of performance measurements "*such as asset utilisation, customer satisfaction, cycle time from order to delivery, inventory turnover, operations costs, productivity and financial results*" i.e., return on assets and return of investment [35]. Performance measures determine the effectiveness of a process or a system or a production line. Therefore, in order to evaluate and improve the performance of a system or a process, it is necessary to measure it in quantifiable terms. Performance measurement is crucial in designing and implementing for improving products and processes and for assessing the result of the improvements, appropriate KPIs are the driving force to execute the performance evaluation package [38]. The importance of measurement portrayed by Lord Kelvin as *"When you can measure what you are speaking about, and express it in numbers, you know something about it."* For the enterprise level, Supply Chain Operations Reference (SCOR) model provides a complete package of KPI metrics that includes the attributes of reliability, responsiveness, agility, cost and assets [39].

Lanz et al. [40] and her research group [41], [42] developed a performance indicators landscape and formed a log of various KPIs that is divided into different categories. Within the manufacturing domain the most important KPIs were found out: *Productivity*, *Manufacturing quality*, *Machine processing time* and *Delivery reliability (on-time delivery)*, *Resource utilization*, *Manufacturing lead time* and *Throughput time*. Those studies based on the interviews with the manufacturing SMEs and relevant expert group.

Kaganski et al. [41] developed and applied KPI selection model to SMEs, which is resulted in a valuable metrics and can be used for performance evaluation of production systems. Kaganski. S., - doctoral thesis [44] resulted in the metrics of thirteen KPIs, top seven KPIs were: *On-time delivery*, *Inventory turnover (throughput), Defects per unit, changes implementation time, Tact time* and *Overall Equipment Effectiveness*. This study particularly focused on SMEs, based on the questioners and different expert groups of academic and production specialist.

2.2.3 Overall Equipment Effectiveness

The common problems faced by manufacturing companies are a waste of time, money, energy and overloaded staff. There are lean measures that can be used to evaluate the performance of manufacturing equipment. However, as the name suggests, OEE is an overall measure that reflects performance from various perspectives. It is a novel technique to measure the effectiveness of a machine or a production system, while it shrinks difficult production problems into simple and provides thorough visualisation of a system performance information [45]. Furthermore, it facilitates systematically analysing the process and finding the potential obstacle areas affecting the effectiveness of production machines.

The OEE metric combined characteristics of reliability, performance and quality into a single KPI and expressed as a percentage. Since it covers such broad inputs, OEE can be a useful measure when trying to improve the management and performance of a critical piece of equipment especially regarding its maintenance, production scheduling, day to day operation and process capability [46]. Moreover, the precise monitoring of the OEE is also desirable as it is a starting point for productivity enhancement of manufacturing equipment, and so, the drive towards operational excellence.

OEE assessment tool derived from the concept of Total Productive Maintenance (TPM) and in this perspective OEE can be reflected to combine the operation, maintenance and management of manufacturing equipment and resources. These applications can be an essential supplement to the existing factory performance measurement system [47]. The purpose of OEE is to identify the sources of lost time and lost production. Since OEE is a measure of production equipment performance, hence needs to be correctly monitored and presented on a daily basis, along with the past history to show the trend, in order to make sure that the equipment/system is working well as far as the Availability, Performance and Quality characteristics are concerned [48]. The OEE as a parameter of effectiveness can be used in a manufacturing environment on different levels. Primarily, OEE can be adopted as a benchmark for measuring the initial performance of an entire production plant. Thus the preliminary OEE values can be distinguished to the future OEE values, and helps to computing the level of improvement made. Secondly, an OEE value, calculated for one production line, can be used to compare line performance across the factory, in that way highlighting any poor line performance. Thirdly, if the production systems process works individually, an OEE measure can identify which production system performance is worst, and therefore indicate where to focus resources [49].

The OEE tool is designed to identify losses that reduce equipment effectiveness. Those losses execute by the events that consume resources but generate no value [50], [51]. Following are the "six big losses", and these losses can also be depicted in Fig. 1.3, where they are shown in integration with equipment and perspectives of performance.

- Downtime Losses – facilitates to calculate the availability of a machine.
- Speed Losses – facilitates to determine the performance efficiency of a machine.
- Quality Losses – facilitates to evaluate the quality level (no. of defects) of a machine.

Different authors support the ideal values of OEE components as [50], [51], [52]: Availability (A) – 90 % or more; Performance efficiency (P) – 95 % or above; Quality (Q) – 99 % or surplus. These levels of availability, performance and quality would result in an OEE of approximately 85 %. However, it is interesting to note that there are different norms in every industry for the standard value of OEE. Therefore, it would appear difficult to form an optimum OEE figure for reference.

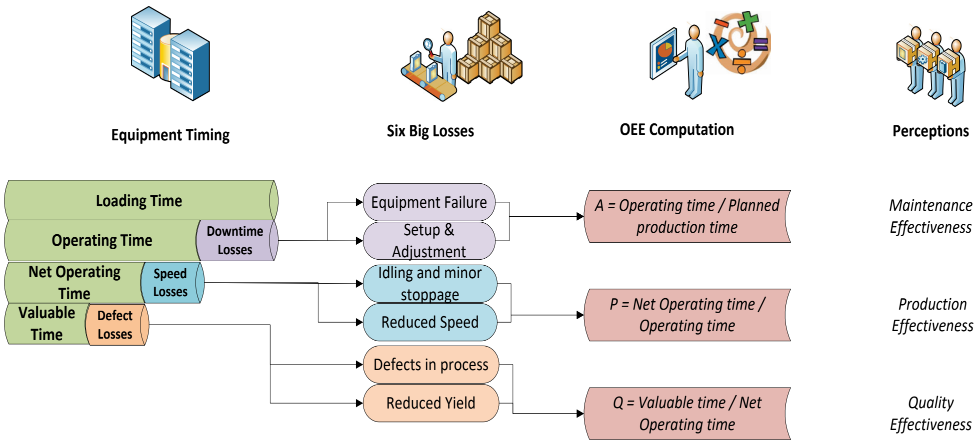


Figure 1.3 OEE Computation Mechanism [48], [51], [52]

2.2.4 System Utilization

System utilisation or system capacity utilisation is one of the operational KPI that determines the quantity of available capacity be used to fulfil the orders demand. It is a useful indicator to evaluate the business and market situations and gives quite a broad picture to the decision makers of an organisation to every level, i.e., operational to strategic [53]. It is a performance measure which determine the optimum time of capacity expansions, access into new markets, departures from the market, cost trends for different manufacturing companies and profitability. Moreover, in operation and production management utilisation of a system can be defined as the percentage of design capacity actually achieved. It can be formulated as the actual output as a percent of design capacity. On the other hand, design capacity defines as the maximum theoretical output of a system in a given time period under ideal condition [54].

It is presented as the ratio of actual output to theoretical output in numbers or the ratio of operational time of a system to the ideal calendar time in which a particular system is used or the proportion of time a production system is used. OEE has only considered the equipment losses, while utilisation consists of schedule losses (plant not open or production not scheduled). Like OEE is measured based on planned production time, and utilisation considered the all available time.

2.2.5 Throughput

Generally, throughput describes as the number of items or material or units of information or data proceeds through a system or process over time.

In manufacturing, throughput time can be referred to the span of time in which a part enters a system until it leaves the system. For some cases, it is also known as lead time (the speed of a process). It is an essential lean KPI and can be calculated directly by measuring actual lead times from the process. Alternatively, an average throughput time can be estimated by Little's law as [38], [55]:

$$\text{Average throughput time} = (\text{Average inventory level})/(Production\ rate)$$

This relationship holds at all levels like it can be used for an individual workstation, a department, a manufacturing plant, or the entire supply chain network. Keep in mind the inventory level and throughput time should be related to the same system.

Based on the analysis of SCOR model, articles by Lanz et al. and research work by Kaganski et al., additionally, individual review of literature about the importance of OEE, Throughput and Resource utilization in a manufacturing domain. OEE, Throughput and Utilization are considered to be appropriate for production systems evaluation.

2.2.5 Business Process Modelling

Several authors define the business process as a regular phenomenon noticeable by steady changes that lead to a particular result; a natural continuing activity or function; a series of actions or operations leading to an end. However, the traditional high-level definition of a business process or a process specifies as the conversion of inputs to outputs [56]. The transformation may classify as physical transformation (Manufacturing), locational transformation (Logistics), transactional transformation (banking and accounting), informational transformation (financial data, sales order etc.).

Business process modelling (BPM) is a form of system analysis; it can serve as an 'as-is' analysis or a 'to-be' analysis of an enterprise. Business processes are supported by information technology (IT) tools and help to simulate a particular process. A business process is a blueprint or template for concrete business process instances; it demonstrates the aspects of decomposition, visualisation and simulation of the workflow [57]. Sometimes business process modelling is needed only to understand relatively high-level details of a system or an enterprise. Value Added Chain (VAC) and Event-driven process chain (EPC) are the modelling techniques used to describe the higher level and lower level actions of an enterprise respectively.

ARIS is a tool that facilitates several process modelling notations including Business Process Modelling Notations (BPMN), VAC, EPC and others [58]. An example of ARIS process chain can be depicted in Fig. 1.4.

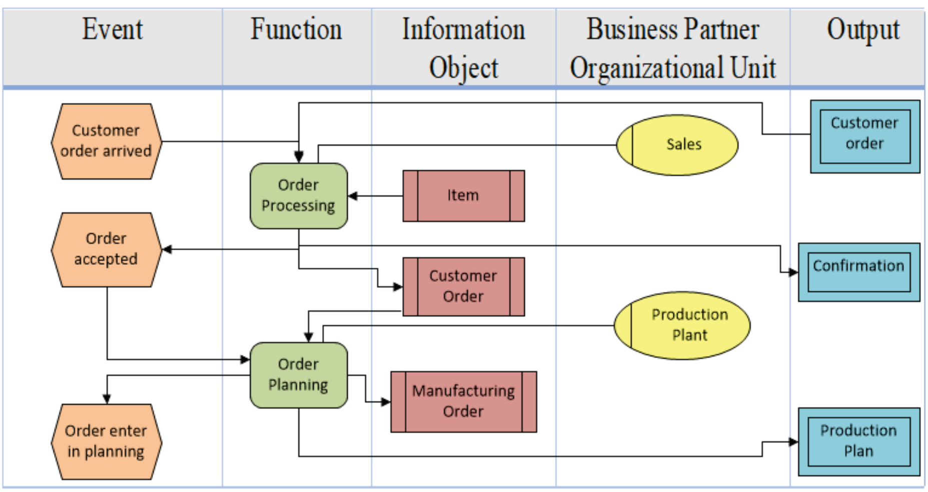


Figure 1.4 Example of ARIS process chain [58]

One more modelling technique known as Integrated Definition Methods (IDEF), it supports structured analysis, it is a modelling language and technique for system analysis in the field of data processing. IDEF0 is used for functional modelling and intended to model the *decisions*, *actions* and *activities* of an enterprise or system. Similarly, IDEF1 is used for information modelling and IDEF1X uses for data modelling such as for the development of information models and database design [58].

Furthermore, IDEF0 is a technique that shows parts, inter-relationships between them and how they fit into a hierarchical structure. The IDEF0 model provides a means for understanding and visualising a system, allow creating a prototype of future systems and capturing needed information in a suitable way [59].

More description and application of IDEF0 is included in the *paper IV.*

2.3 IoT Concept and Applications

The exposure of the internet has altered the daily business and personal lives during past years. It is continuing similarly and perhaps in the future also as it can be depicted from the current trends. IoT is an expansion of the internet; it provides instant access to information about physical objects and leads to innovative services with high efficiency and productivity [60]. According to Scientific service of the German government, the concept to IoT defines as "*the technical vision to integrate objects of every kind into a universal, digital network. Equipped with a unique identity they interact in a smart environment. This creates a connection between the physical world of things and the virtual world of data.*" [61]. Moreover, the internet of services refers to the growing trend of offering services online. The increasing networking radically changes the business process. The potential of IoT applications affects all areas of business. The possible applications of IoT are illustrated in Fig. 1.5.

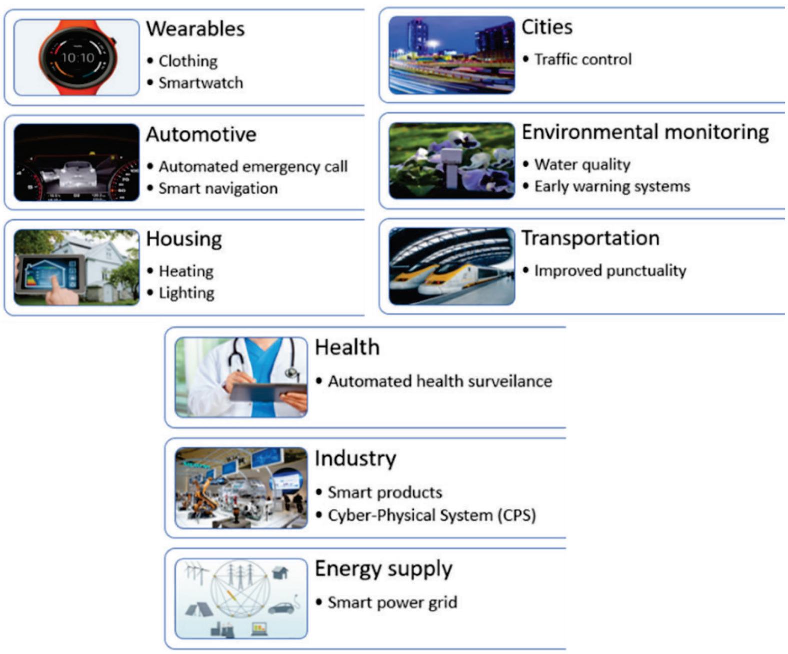


Figure 1.5 Possible applications of IoT [60], [61]

The digital transformation of industry enabled by the IoT permits new ways for businesses to connect and co-establish value. New data-driven strategies will support the enterprises to evaluate their performance by gathering and analysing data through the whole product and project lifecycle [62]. Furthermore, the fundamental aim of IoT applications in manufacturing also known as Industrial Internet of Things (IIoT) is to realise smart factories, in which machines and resources communicate and are connected in a network. For that purpose, production tools, resources and existing IT tools of an enterprise should be connected to the internet directly or through external adapters. Subsequently, production tools/systems will be transformed into "cyber-physical system" (CPS) upgraded with knowledge provided by data capturing and analysis [63]. Therefore, the advent of Industrial Internet of Things (IIoT) and the fourth industrial revolution has led production systems developing into digital ecosystems, where IIoT and Big Data play a vital role to manage the volume and variety of data at high rates [64].

2.3.1 IoT and Industry 4.0

The internet of things is perceived as a driver of *industry 4.0*. *I-scoop* guide to industry 4.0 describes *"Industry 4.0 is the fourth industrial revolution in manufacturing and industry. It portrays the current industrial transformation with automation, data exchanges, cloud, cyber-physical systems, robots, Big Data, Artificial Intelligence (AI), IoT and semi-autonomous industrial techniques to understand the smart industry and manufacturing goals in the intersection of people, new technologies and innovation"* [65].

Following are the organisational principles of industry 4.0 [61]:

- Flexible – Flexible organisations with flat hierarchies
- Modular – Companies comprise of flexible, scalable modules
- Decentralised – utilisation of decentralized global resources
- Open – Information exchanged within the network

Comparison of formerly described industrial revolution (industry 3.0) and the recent industry 4.0 can be depicted in Fig. 1.6. Reduction in complexity under industry 4.0 as many decisions are made decentralised. *Digital interaction* is the most critical component of industry 4.0 that complements the automation of industry 3.0.

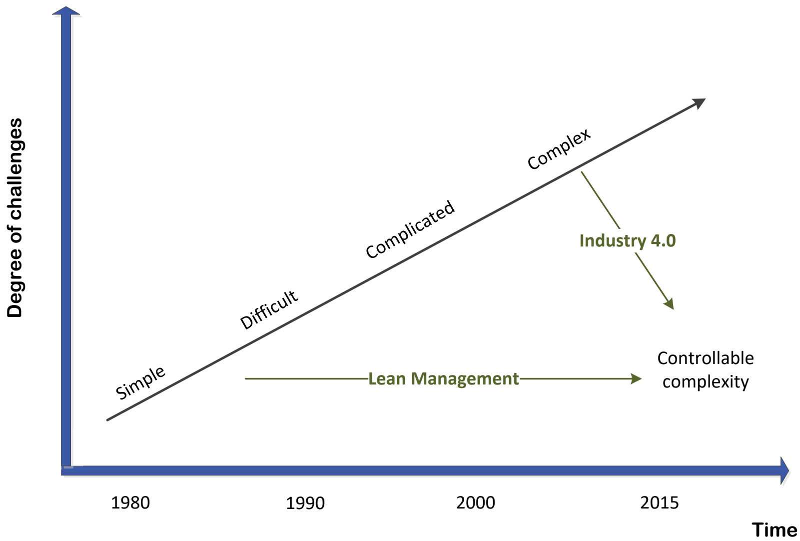


Figure 1.6 Correspondence of industry 3.0 & industry 4.0 [61]

In the technological context digitalisation is a transfer of analogue technologies to digital technologies. However, different literatures define digitalization differently, in a company context it describes as the gradual penetration of all social areas by digital systems and displays, likewise the corresponding computer-based and virtual methods of work and conduct.

Under the digitalisation and the concept of IIoT, the horizontal and vertical integrations are interpreted as:

Horizontal integration – represents as the value creation process within a value creation network, in which all objects departments and all companies within the network, exchange data with each other [65].

Vertical integration – represents as the linking of all information and communication technologies as well as the operating technology. The product, the sensors on the machine included the Enterprise Resource Planning (ERP), which means systems are connected and have access to all data [65].

Digital Manufacturing – according to Siemens "*Digital manufacturing* is the use of an integrated, computer-based system comprised of simulation, 3D visualisation, analytics and collaboration tools *to create product and manufacturing process definitions simultaneously."* Allows manufacturing companies to achieve time-to-market, volume goals, and cost savings by reducing expensive downstream changes [66]. Design and analysis of production systems can be performed through digital tools which ultimately help the business processes throughout the product life-cycle [67].

2.3.2 Cyber-Physical Systems

They are the basis of IoT. The National Institute of Standards and Technology (NIST) describes "*Cyber-Physical System (CPS) as the IoT which involves connecting smart devices and systems in diverse sectors like transportation, energy, manufacturing and healthcare in fundamentally new ways. Smart cities/communities are increasingly* *adopting CPS/IoT technologies to enhance the efficiency and sustainability of their operation and improve the quality of life*" [68].

The attributes of CPS are: the sensors of the object (device) collect all process data, wireless connection of all objects, Human Machine Interfaces (HMI) and self-optimised systems [69]. The similar way manufacturing sector is at the inception of adopting CPS to enhance the efficiency, productivity and sustainability of their operations and production systems, known as Cyber-Physical Production System (CPPS).

The manufacturing-oriented CPS is called CPPS, which holds the attributes of robustness, autonomy, self-organisation, transparency, predictability, efficiency, interoperability, global tracking and tracing [63]. The basis of CPS highlighted by [70] as the representation of the physical system in the virtual world and the virtual system can be presented in the physical world.

2.3.3 Industry 4.0, Lean Production and Real-time Visualization

Provision of real-time and goal-oriented information across all hierarchy levels, i.e., from shop floor to top floor of an enterprise is a significant success aspect for manufacturing companies. It facilitates companies to be agile and efficient in their processes. The digital screen displays using dashboards highlight this challenge and support perceptive monitoring and visualisation of production KPIs and business performance information [71].

Moreover, the traditional way to a collection of factory data has required manual reporting work or a large integration effort of machine specific controllers. With the advent of Industrial Internet Technologies, which are providing new possibilities with data integration platforms and communication interfaces, it is possible to accomplish real-time visualisation of the status of a production system and production data with fewer efforts. Real-time monitoring and visualisation are shortly discussed in the *paper V.*

Today we are facing a new industrial paradigm which is mostly known as the fourth industrial revolution or Industry 4.0, and it describes the vision of the future production. However, the lean production paradigm became the key approach to produce highly efficient processes in the manufacturing industry since the early nineties. Behind the success of the lean approach – its capability to reducing complexity and avoiding non-value added activities [72].

Recent developments are addressing to combine the industry 4.0 (Industrial Internet technologies) new solution with lean production to have fruitful outcomes. Latest research integrate the lean tools and techniques such as Kanban and JIT to Cyber-Physical Production System (CPPS) [73]. The results are coming in the form of a smart operator, smart product, smart machine, smart planner that facilitates to cut-down the famous lean wastes [74]. Nevertheless, a holistic framework is required to support the integration of Industry 4.0 solution to lean production, and different research works are ongoing in this direction.

This thesis work also describes how the lean KPIs like OEE can be integrated with Industry 4.0 concept such as data acquisition and processing, Human-Machine interaction via the dashboard, for the real-time visualisation of automated production systems.

Table 1.3 Different literatures on VE with respect to process modelling, risk assessment and performance of production systems via IoT

Literature	Virtual Enterprise		
	Process Modelling	Risk Assessment	Performance of PS via IoT
Camarinha-Matos et al. [15], [75], Benjamin Knoke et al. [76], Jens Ziegler et al. [77], Vladimir Modrak et al. [78]	+	-	-
Gang Liu et al. [79], Min Huang et al. [80], O.C. Alves Junior et al. [81], João Rosas et al. [82]	+	+	-

Similarity (+)
Gap (-)

3. Results of Research

This chapter describes the results of research work and case studies, it includes a proposed reliability management approach for a virtual enterprise of SMEs in a manufacturing domain. The approach consists of two concepts which have developed in this research.

3.1 Development of Reliability Management Approach

A conceptual model for collaborative project realisation by SMEs is shown in Fig. 3.1. The model comprises of four stages, stages one and two correspond to the long-term strategic alliance in the form of SPN establishment. The subsequent stages three and four are relevant to the creation and operation of a goal-oriented network, i.e., VE. This thesis is contributed in the fourth stage (VE management) of the conceptual model.

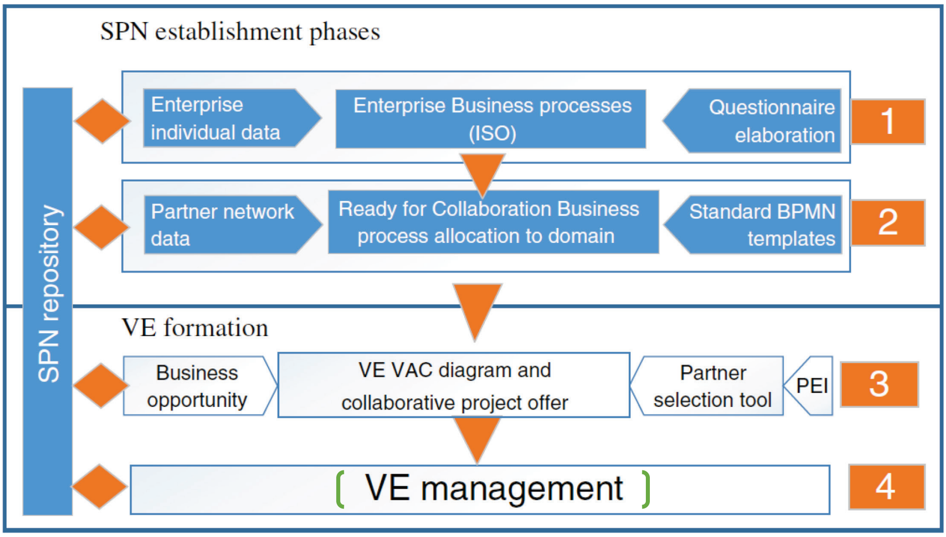


Figure 3.1 Conceptual model of sustainable realization of collaborative projects [II]

However, the questionnaire developed in the first stage, which is about the services that an enterprise could provide, also reflects the enterprise business process. It is extended in the fourth stage in order to include the questions about possible risks for a VE phases, and KPIs related to production systems.

The first stage questionnaire consist of the following questions and respond by SMEs: (https://www.surveymonkey.com/r/MLMYFVY)

Which of the business services your company wants to export to SPN?
Your company location (address, office, workshop, etc.)
What operations are you ready to subcontract?
What are the certificates own by your company?
What are the diplomas or achievements your company own?
Possibility of communication with your company (phones, e-mail, faxes, etc.).
Response contact person at Collaboration Network (Name, Surname, Contact phone, e-mail).
What are the business objectives of your company?

More questions were added during the third and fourth stages, the target group are manufacturing SMEs, group of managers of SMEs and relevant academic staff working on VE. The questionnaire is as follows:
(https://www.surveymonkey.com/r/68JNLCL)

What kind of risks does the realization phase may face? (rate the likelihood)

What kind of risks does the formation phase may face? (rate the likelihood)

What kind of risks does the action phase may face? (rate the likelihood)

What kind of risks does the closure phase may face? (rate the likelihood)

What are the KPIs importantly related to your manufacturing equipment/production system/line?

What information system(s) are you using for management of your business process? (Any IoT application using for monitoring purpose or willing to use it in future)

The reliability management approach for a VE can be depicted in Fig. 3.2. It consists of two concepts. First is the risk assessment of a VE lifespan, VE has been described by the as project-based enterprise. Where R_Z reflects the overall risk value, which may possess by a VE. The second concept is the performance evaluation of production systems in a VE, where P_S refers to the performance factor of production systems. Finally, V_R denotes to the reliability factor of a virtual enterprise, which is the combination of R_Z and P_S respectively as defined in equation 3.1.

$$V_R = \{ R_Z , P_S \} \qquad (3.1)$$

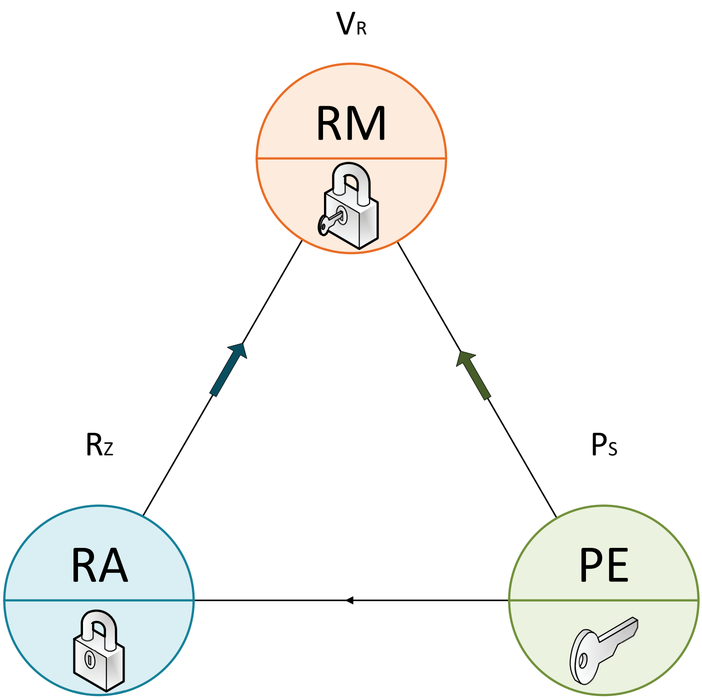


Figure 3.2 Reliability management approach for a VE

3.1.1 Risk Assessment Concept for VE

Based on the literature review of the related techniques as discussed in the previous chapter, a risk assessment concept for a lifespan of VE has developed, which comprises of the following steps as shown in the Fig. 3.3.

- Defining the phases of existence of a VE through the process modelling activity
- Risks identification and classification by the brainstorming activity
- Estimation and evaluation of risks with the help of risk matrix
- Determination of overall risk level of a VE through the FTA
- Improvement and monitoring using IoT concept

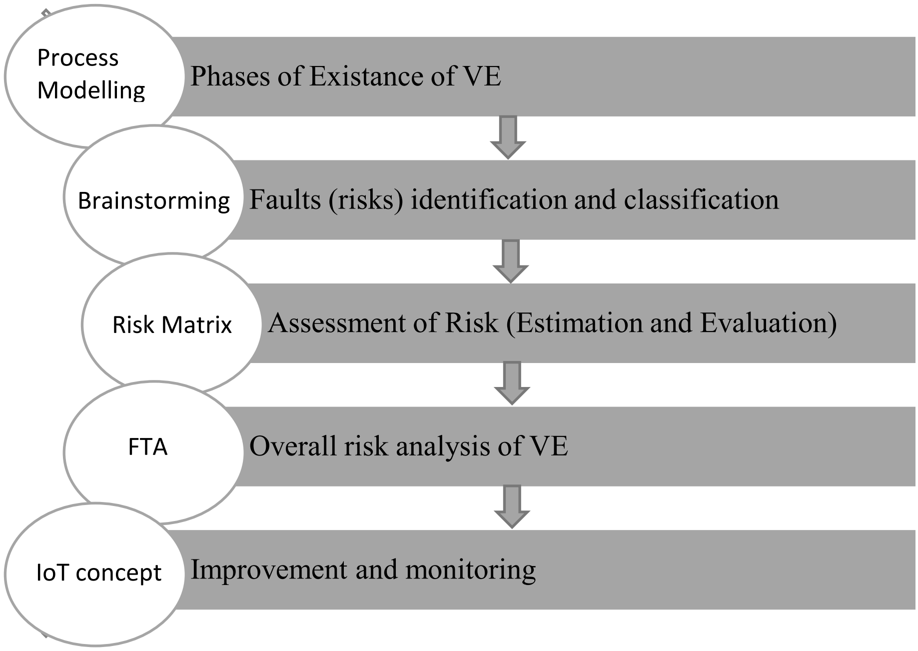


Figure 3.3 Schematic of Risk Assessment concept for VE [I]

Phases of the existence of a VE – The lifespan of a VE is divided into four phases, realisation phase, formation phase, action phase and closure phase. The description is provided in the (Paper I).

Risk identification and classification – The internal risks that a VE can possess during its lifespan are identified in the form of hierarchical structure. There are four layers (phases) in the hierarchical risk model such as realisation, formation, action and closure. Each layer has its sub-groups as illustrated in Fig. 3.4, where sub-groups are having its risk factor (Z_{11}, Z_{12}); (Z_{21}, Z_{22}, Z_{23}); (Z_{31}, Z_{32}, Z_{33}, Z_{34}); (Z_{41}, Z_{42}), respectively and *Z* is the overall risk factor for the lifespan of a VE (Paper I).

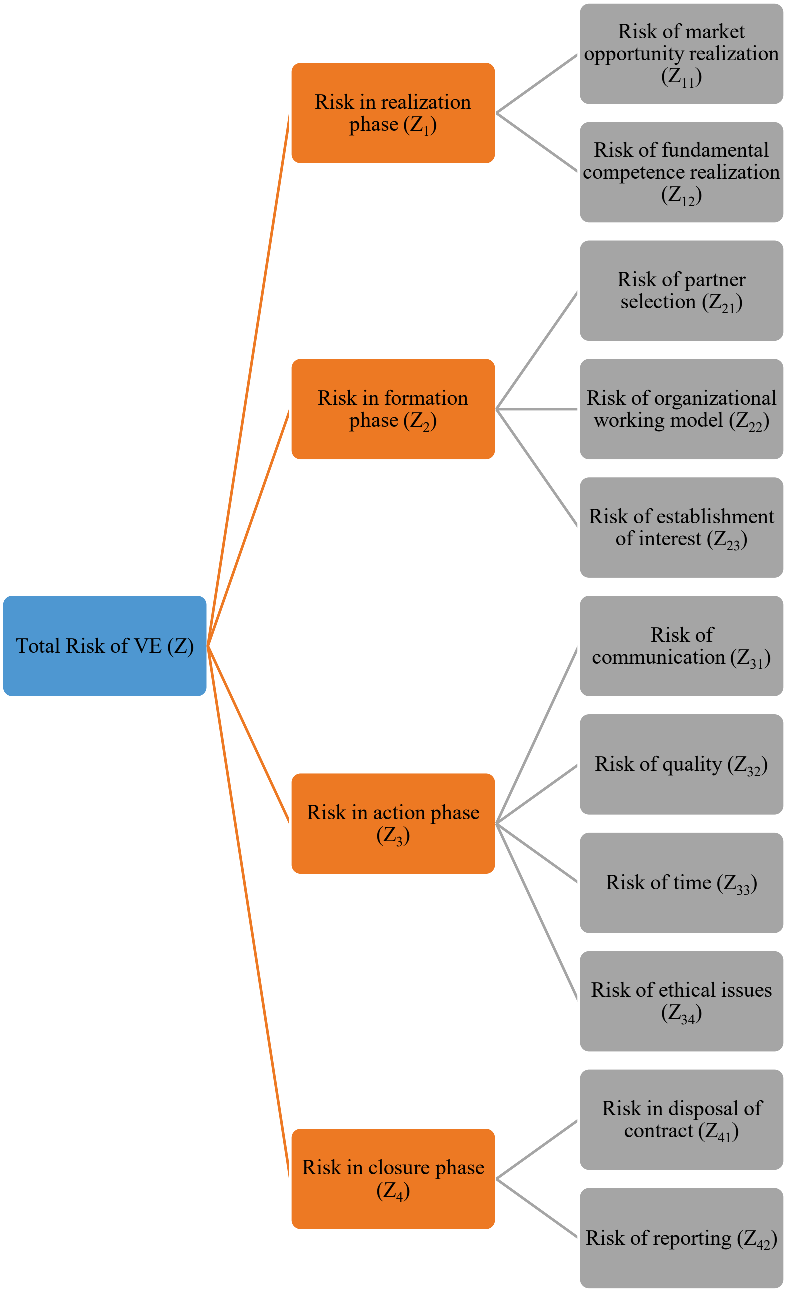


Figure 3.4 Hierarchy of identified risk factors [I]

Risk Estimation and Evaluation – Risk assessment contains an evaluation of possible identified risks, and the losses may occur due to these risks, which enables an enterprise to take effective measures in order to avoid and control risks. After the development of a hierarchical system for the identification, description, and assessment of VE risks; risks factors are evaluated using a semi-quantitative method based on a risk matrix. The main idea is to estimate the four risk driven factors and then to integrate them to calculate the entire system factor.

Since risk (R) is the combination of probability (P) of an event fails and its impact (I). Hence, the risk equation can be depicted as (Paper I & III):

$$R_f = P_f \times I_f \qquad (3.2)$$

For the estimation probability and impact, a scale is a set-up from 1 to 5 that can be seen in Fig. 3.5, where 1 is the lowest and 5 is the highest possible value. Moreover, a risk matrix as shown in Fig. 3.6 is used to evaluate the risk level, which shows the risk associated with the failure based on the ranking of probability and consequence. The numbers represent the risk values ranging from 1 to 25. Risks located at the top right corner of the probability and impact matrix have to be handled first, and the same is true for all the risks with high impact values (Paper I & III).

Probability	1	< 20%
	2	
	3	50%
	4	
	5	> 80%
Impact	1	Low
	2	
	3	Medium
	4	
	5	High

Figure 3.5 Scale of probability and impact ratings [I]

IMPACT						
	High	5	10	15	20	25
		4	8	12	16	20
	Medium	3	6	9	12	15
		2	4	6	8	10
	Low	1	2	3	4	5
		0	20	40	60	80 100
		PROBABILITY				

Figure 3.6 Risk matrix for risk level evaluation [I]

Overall Risk of a VE – Due to the hierarchical structure of the risks, modelled for a VE. FTA is used for the estimation of overall risk and determine the reliability of a VE, Fig. 3.7 illustrates the FTA model for a VE.

The likelihood of the top event (Z) for the VE can be represented as equation 3.3:

$$P_Z = P_{Z1}(\sum P_{Z1i}) \cap P_{Z2}(\sum P_{Z2i}) \cap P_{Z3}(\sum P_{Z3i}) \cap P_{Z4}(\sum P_{Z4i}) \qquad (3.3)$$

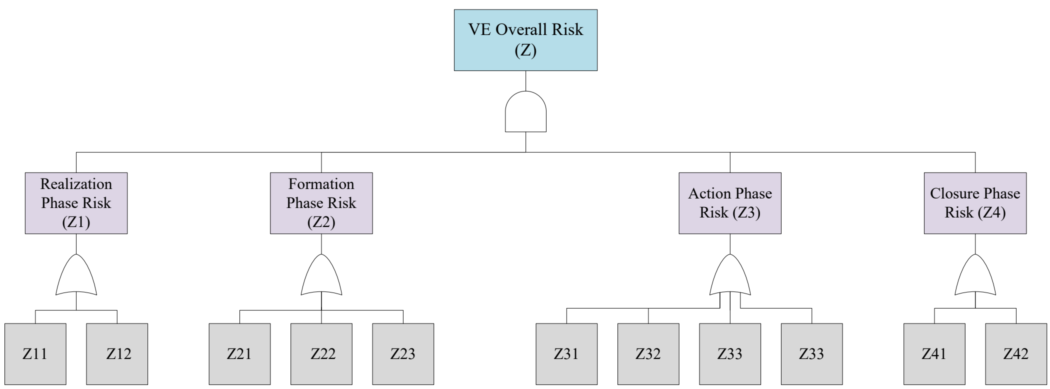


Figure 3.7 FTA model for a VE

IoT-based Monitoring – For the mitigation of risks, an IoT-based monitoring concept has been proposed and can be seen in Fig. 3.8. Monitoring of the business processes of each VE partner can be done by embedded electronics such as sensor-enabled technologies and tools. These tools could be wireless technology, barcodes, RFID tags, Quick Response (QR) codes, etc., usually known as the IoT. Each business process has its smart sensor that transfers real-time process information. The process data collected from the sensor readers stored into the cloud-based data storage (Paper I). Moreover, the responsible person from each SME of the VE would log the risks and communicate to the VE cloud.

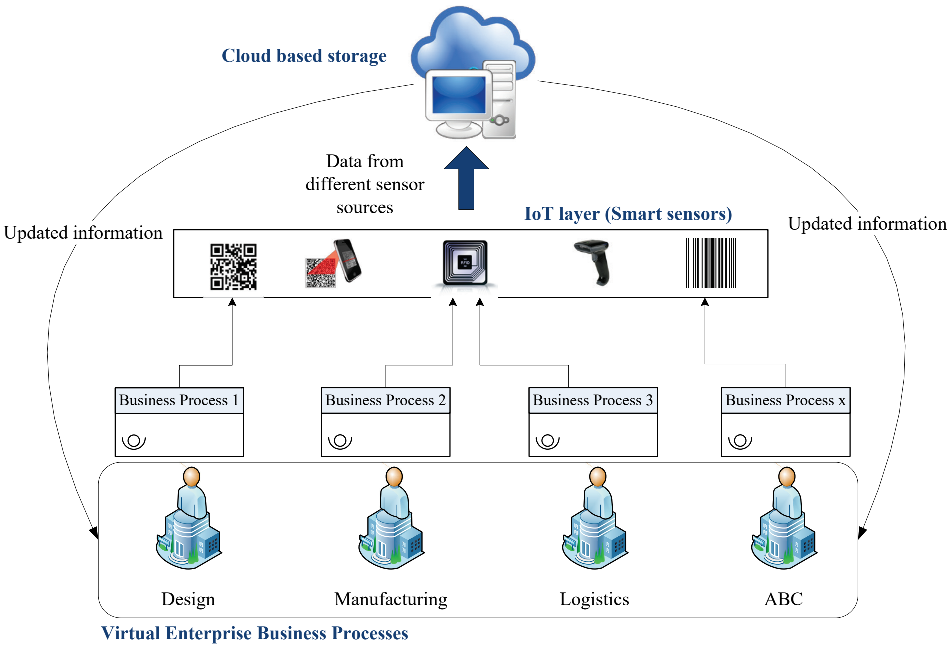


Figure 3.8 Concept of IoT-based monitoring within VE [I]

3.1.2 Production Systems Performance Evaluation in VE

For the stability of a VE, one of the key elements is the evaluation of the production systems and resources that SMEs possess. If the efficiency of a production system cannot be assessed, then it cannot be properly controlled, which leads to waste of time, money, energy and overloaded staff (Paper V). Therefore, a performance evaluation concept for production systems has developed in this study, which consists of the steps as follows and shown in Fig. 3.9. It is a continuous process.

- Realise and Define System
- Selection of KPIs
- Process modelling
- Data collection
- Monitoring & Visualization (Real-time)

Figure 3.9 Performance evaluation concept for production systems [V]

Realize & Define a System – Definition of a system involves its nomenclature and mechanism of working. Possession of production systems in a SME network within the context of VE should be described in this step. Since the VE idea is adopted from the SPN, therefore Fig. 3.10 describes how the VE forms and works, establishes the Value-Added Chain (VAC) and where the production systems are positioned (Paper V).

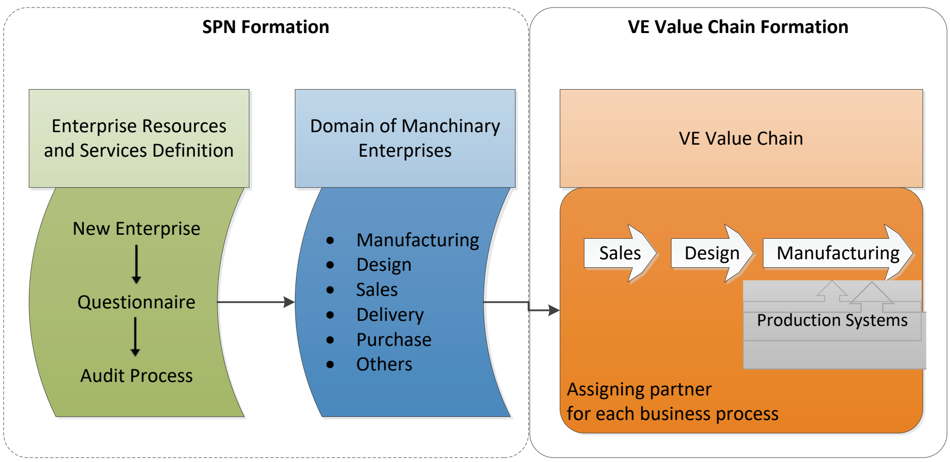


Figure 3.10 VE formation as a SME network [V]

Selection of KPIs – Choosing the right KPIs for the evaluation of production systems is one of the major steps of the concept. The main focus of this study is to link lower level (shop floor level) KPIs to the Upper level (Strategic level). As production systems are located at the lower level of an organisation and for the reliable management of a VE, lower level KPIs should be connected and featured at the upper level of the VE. Thus, they are available to visualise in a network. Based on the different literatures mentioned in the literature review section of KPIs, also referred in the (Paper V), the KPIs are categorised into three levels.

The hierarchy shows the levels of KPI mapping and process modelling Selected KPIs of each level 1, 2 and 3 are illustrated in the form of metrics as depicted in tables 3.1, 3.2, 3.3 and 3.4 respectively, see Fig. 3.11. L1 is divided into two groups i.e., level 1a and 1b, level 1a matrix designated for whole value chain of VE that includes main processes of sales, manufacturing and logistics etc. While matrix 1b represents the process of manufacturing, specifically the production system or manufacturing equipment efficiency/productivity matrix. As this study is focused on the performance evaluation of production systems, levels 2 and 3 are described within the domain of manufacturing equipment. Furthermore, the relationship between KPIs of all levels is portrayed in the Fig. 3.12 (Paper V).

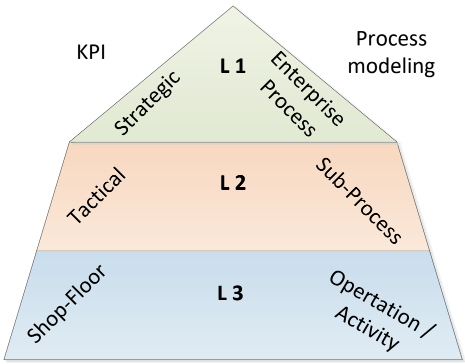


Figure 3.11 Levels for KPIs and process modelling [V]

Table 3.1 Level 1a matrix of KPIs for whole value chain of VE [V]

Performance Attributes	Performance Indicators (KPIs)	ID	Description	Formulation	Units
Reliability (RL)	Order Fulfillment	RL1	Right quality and quantity as required	(Total PO / Total NO) x 1oo	%
Responsiveness (RS)	Order Fulfillment Cycle Time	RS1	Speed to perfrom task	(Sum ACT of OD) / (Total OD)	Days; Hr
Agility (AG)	Flexibilty	AG1.1	Ability to and speed of change	Minimum time to achieve unplanned tasks or orders	Days; Hr
	Overall Risk Value	AG1.2		(P of RE) x (Impact of RE)	-
Cost (CO)	Cost to Serve	CO1	Labour, Material and Transportation cost	Labor + Material + Equipment + Transportation Costs	€
Asset Efficiency (AE)	Return on Investment	AE1	Ability to efficiently utilize assets (inventory & Resources)	(Revenue – Cost) / [(Inventory) + (Receivable – Payable)]	€

PO = Perfect Order NO = Number of Orders OD = Orders delivered

P = Probablity RE = Risk Event Hr = Hours

Table 3.2 Level 1b matrix of KPIs for a production system/equipment [V]

Performance Attributes	Performance Indicators (KPIs)	ID	Description	Formulation	Units
Equipment Reliability & Responsiveness	Throughput time	ER1.1	On time - Desired time to produce a product	(Process + Move + Queue + Inspection times) / (Total finish products)	Hr;min;sec
	OEE	ER1.2	Overall Equipment Effectiveness - Estimate an equipment truly productive time (productivity)	(Availability factor x Performance factor x Quality factor) x 100	%
	Utilization	ER1.3	Proportion of time an equipment is used	(Operational Time / Calendar Time) x 100	%

Table 3.3 Level 2 matrix of KPIs for a production system/equipment [V]

Performance Indicators (KPIs)	ID	Description	Formulation	Units
Availability (A)	ER2.1	Time an equipment is actually available after downtime losses - convey maintenance effectiveness	(Operating time / Planned production time) x 100	%
Performance (P)	ER2.2	Time an equipment is operating on actual speed rather on ideal speed - speed losses - convey production effectiveness	(Actual Production Rate / Ideal Production Rate) x 100	%
Quality (Q)	ER2.3	Time an equipment is taking to produce good quality product only - defect losses - convey quality effectiveness	[(Total product produced - Rejected product) / (Total product produced)] x 100	%
Planned Production Time (PPT)	ER2.4	Difference of Schedule (shift) time and planned downtime (breaks time)	Total shift duration - Planned downtime	Hr;min;sec
Operating Time (OT)	ER2.5	Difference of planned production time and unplanned downtime (breakdown/failure)	PPT - Unplanned downtime	Hr;min;sec
Actual Production Rate (ACT)	ER2.6	Ratio of total product produced to operating time	(Total product produced / OT)	Product/min

Table 3.4 Level 3 matrix of KPIs for a production system/equipment [V]

Performance Indicators (KPIs)	ID	Description	Units
Total Products Produced	ER3.1	Total number of product produced on production line or system	-
Finished Products	ER3.2	Number of good quality product produced	-
Rejected Products	ER3.3	Number of bad quality product produced	-
Failure or breakdown Time	ER3.4	Time to repair or fix a failure	Hr;min;sec
Activity Processing Time	ER3.5	Operational time of each activity or workstation or resource	Hr;min;sec
Ideal Production Rate	ER3.6	Product produced at maximum running speed of an equipment	Product/min
Total Run Time	ER3.7	Total running time of production line or production system	Hr;min;sec
Non-Processing Time	ER3.8	Non-operational time, queuing time, idle time of resources	Hr;min;sec

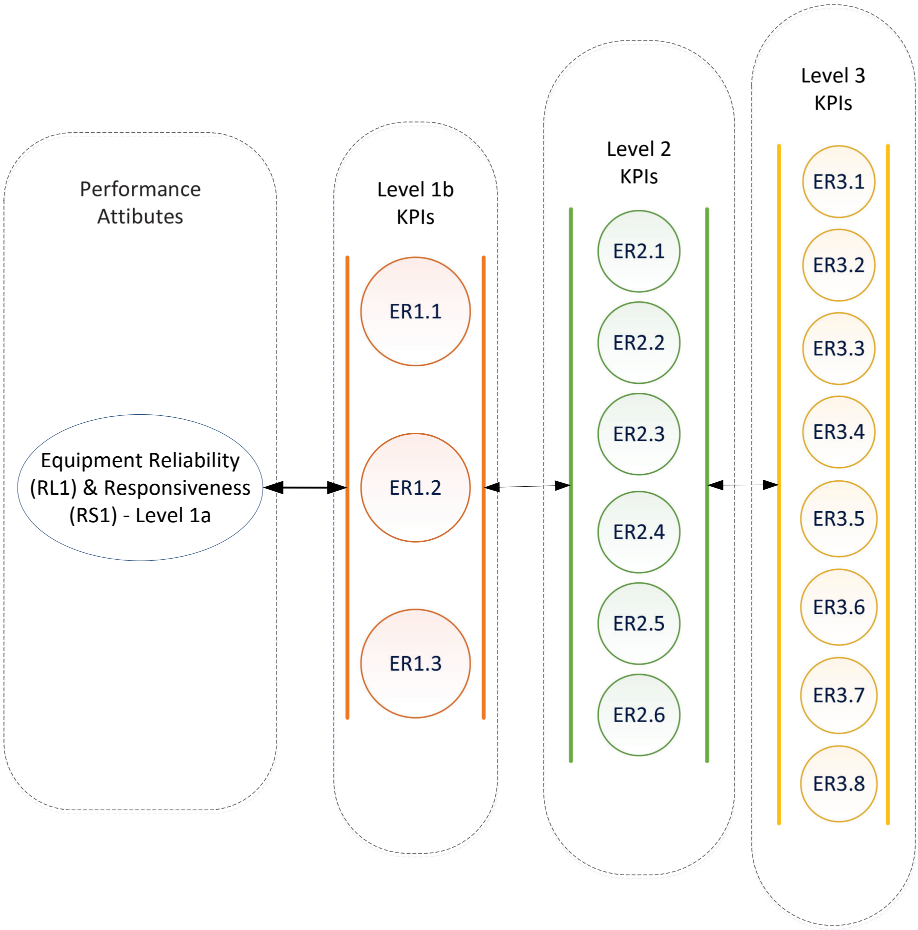


Figure 3.12 Hierarchical linking between KPIs at all three levels [V]

Process Modelling – Process modelling is an essential component of a system study and it helps to provide the description of business processes. Process modelling not only used to model the business process value chain, but also to model the lower level activities and process steps. The purpose of process modelling is to define the enterprise structure, process sequence with inputs and outputs, responsibilities and the process owner (Paper IV and V). An illustration of process model levels can be seen in the Fig. 3.13.

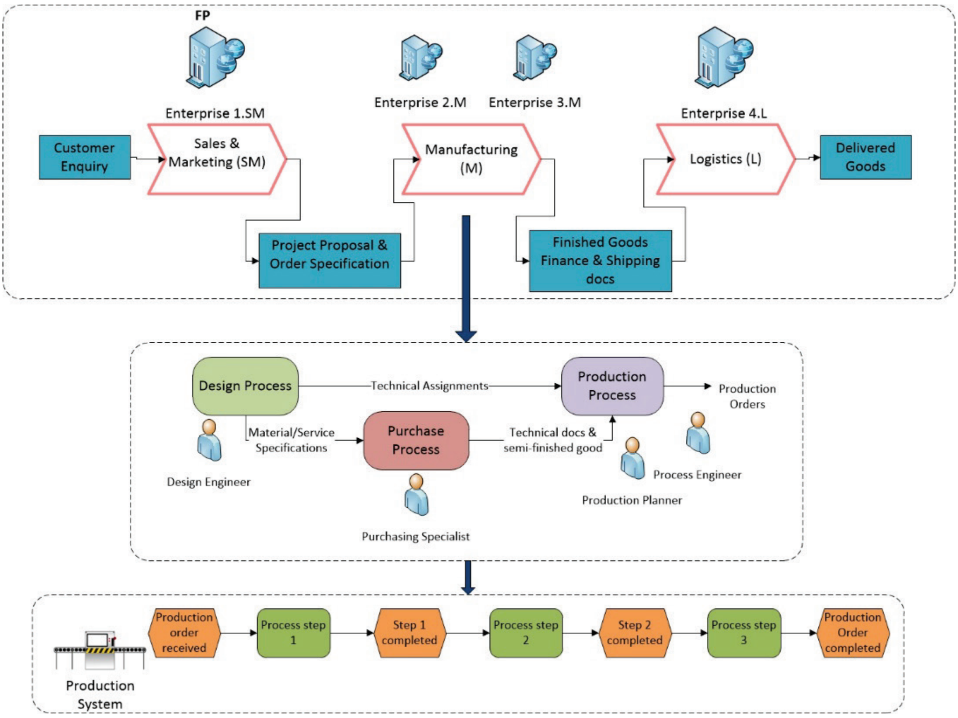


Figure 3.13 Levels of process models [V]

Data Collection – It states a procedure for acquiring data from production systems and identifies the parameters that are needed to measure the defined KPIs. Due to the modern era of manufacturing and digitalisation, production systems are often embedded in smart sensors and electronics. Therefore, the IIoT approach is used for data collection (Paper V).

Real-time Monitoring and Visualization – This step facilitates effective decision making and to provide the best insight about the KPIs to the strategy makers. As conveying of dynamic real-time production data and related KPIs is necessary, it can be achieved through an informative visual dashboard and IoT platform can be used for the execution (Paper V).

Performance Factor of Production Systems – Based on KPIs defined in the table 3.2, which reflects equipment (systems) reliability and responsiveness. The mathematical model for performance factor 'P_s' can be formulated with the objective functions as follows:

- $F_1(\overline{x})$ - Throughput or Production rate (units/Hr, min)
- $F_2(\overline{x})$ - OEE (%)
- $F_3(\overline{x})$ - Utilization (%)

Functions have different units, range and should be normalised by applying the following equation:

$$f_i(\bar{x}) = \frac{F_i(\bar{x}) - \min F_i(\bar{x})}{\max F_i(\bar{x}) - \min F_i(\bar{x})} \quad (3.4)$$

In equation 3.4 $\bar{x}$ stands for the vector of design variables and the values $maxF_i(\bar{x})$ and $minF_i(\bar{x})$ are estimated values for function maximum and minimum, respectively. Moreover, equation (9) is applied to objectives subjected to maximization $F_1(\bar{x})$, $F_2(\bar{x})$, & $F_3(\bar{x})$. Thus, the normalized objective function $f_i(\bar{x})$ can be ranged from 0 to 1.

The considered objectives are not conflicting and can be verified by performing a pairwise analysis of the objectives. Therefore, the objectives can be combined into one by applying a weighted sum technique. Hence, the performance factor 'P_s' can be expressed as:

$$P_s = \sum_{i=1}^{N} c_i \; f_i(\bar{x}) \quad (3.5)$$

In Equation 3.5 N = 3, i.e., a number of objectives and c_i stands for the weight of the objective, determined for a particular production system or line based on the literature searched and opinions from the expert in the related field.

3.2 Outcome of Case Studies

To understand the relevance of the developed concepts, in this chapter the case studies of both concepts are described. A computational case study has performed for the risk assessment concept of the lifespan of VE, which resulted in the computed value of R_Z factor. Followed by a case study for performance evaluation of production systems in a VE is elaborated and P_S factor has estimated.

3.2.1 Risk Assessment of VE – Case study result

The summarised results of the risk assessment concept that include the estimation of each subsystem risk factor with their likelihood, probability factor and impact factor are shown in Table 3.5. Equation 3.2, figures 3.4, 3.5 and 3.6 are used to form the Table 3.5. In order to analyse the variation in likelihoods, the impact factor of each risk event is assumed to be 3 (medium), and the initial likelihood values are based on the survey conducted among SMEs, in addition where needed, academic experts opinions also included. The initial questionnaire comprised of only likelihood estimation of risks, as to assess the variation in likelihood factor.

Table 3.5 Subsystem risk factors estimation [I]

Risk factor	Likelihood	Probability factor	Impact factor	Risk level
R_{Z11}	0.25	2	3	6
R_{Z12}	0.1	1	3	3
R_{Z21}	0.3	2	3	6
R_{Z22}	0.2	2	3	6
R_{Z23}	0.1	1	3	3
R_{Z31}	0.4	3	3	9
R_{Z32}	0.15	1	3	3
R_{Z33}	0.2	2	3	6
R_{Z34}	0.1	1	3	3
R_{Z41}	0.15	1	3	3
R_{Z42}	0.1	1	3	3

Since the risks within VE are classified hierarchically. Therefore, FTA was done to estimate the overall probability factor of upper-level risk events. In the end, it helped to estimate the overall risk factor of the lifespan of a VE. Equation 3.3 was implemented to execute the FTA as shown in Fig. 3.14 and to form the table 3.6.

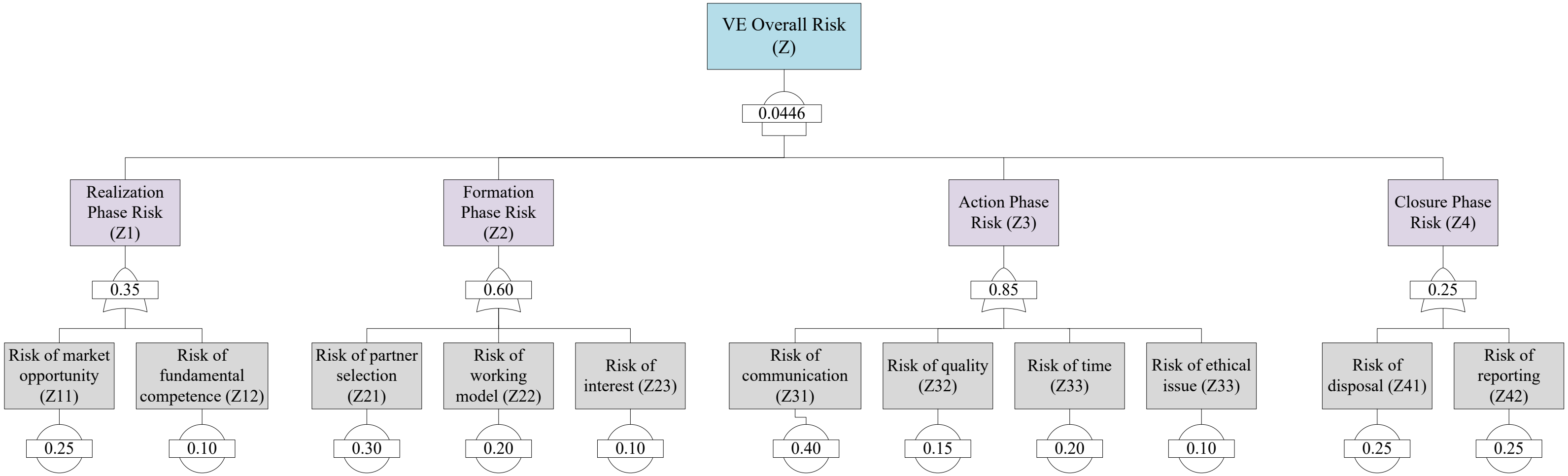


Figure 3.14 Fault Tree Analysis of the lifespan of a VE [I]

Table 3.6 Overall risk level estimation [I]

Risk factor	Likelihood	Probability factor	Impact factor	Risk level
R_{Z1}	0.35	2	3	6
R_{Z2}	0.60	3	3	9
R_{Z3}	0.85	4	3	12
R_{Z4}	0.25	2	3	6
R_{Z}	0.04	1	3	3

It was found that the risk level of the action phase of VE is higher and it was because of the risk value of the communication activity. Therefore, the proposed IoT-based concept for risk mitigation of action phase is appropriate.

3.2.2 Performance Evaluation of Production Systems – Case study result

In the recent digital era, the manufacturing SMEs possess the automated production systems/line and they are willing to adopt new technological IoT based solution. New technologies reduce the required integration effort and provide unexplored potential for advancements in SMEs. Therefore, automated production systems were selected for testing the developed concept. The layouts of automated production systems (lines) that were used for a case study can be depicted in Fig. 3.15 (a & b) and 3.16 (a & b) respectively.

The production system 1 as shown in the Fig. 3.15a is the updated version of a relatively old production systems (the layout was created on Visual Components 4.1), the improved version have *Arduino microcontrollers* and the *Raspberry Pi3* as a single board computer to collect data from microcontroller. The performance evaluation concept is partially tested in this system, it is located in Tallinn University of Technology and used for academic research work.

The production system 2 as shown in Fig. 3.16a is highly automated FESTO production system, it is the "Festo didactic training line" located in Seinajoki University of Applied Sciences (SeAMK), which was used to validate the performance evaluation concept. It also supports the adaptation of the simulation technology in local manufacturing SMEs. The author of the thesis was a visiting researcher for a semester in the Tampere University of Technology (TUT) and SeAMK. Where he grasped the opportunity to implement the concept with the help of the research group at TUT.

Working Principle of Production System 1

The system starts with the parts being dispensed from the part dispenser on the first conveyor. As soon as the part reaches the end of the first conveyor, the robot 1 picks and places the part onto the second conveyor with a gauge sensor. Once the part reaches the end of the second conveyor, the part dimension (size) has been recorded. The robot 2 picks and places the part from the second conveyor into the CNC milling machine. As the arm gets out of the CNC mill, the milling processes begin according to the program. The part is taken out by the same robot 2 and placed on the indexing table at its respective place. The whole process is automatic, but the system needs human assistance for putting the parts in the dispenser, taking the finished part of the indexer and changing the tool of the mill.

The direct process controller of an individual component of the production system 1 is straightly communicated with another components controller. Furthermore, each component process controller of the system should also communicate with supervisory control. The purpose of the supervisory control in the suggested architecture is to act as Human Machine Interface (HMI), data acquisition unit and data server. The distributed control and transmission of data from component to component facilitate in the faster processing speed of the system. The separate role of each component allows reprogramming components individually. The control architecture of the system can be seen in Fig. 3.15b.

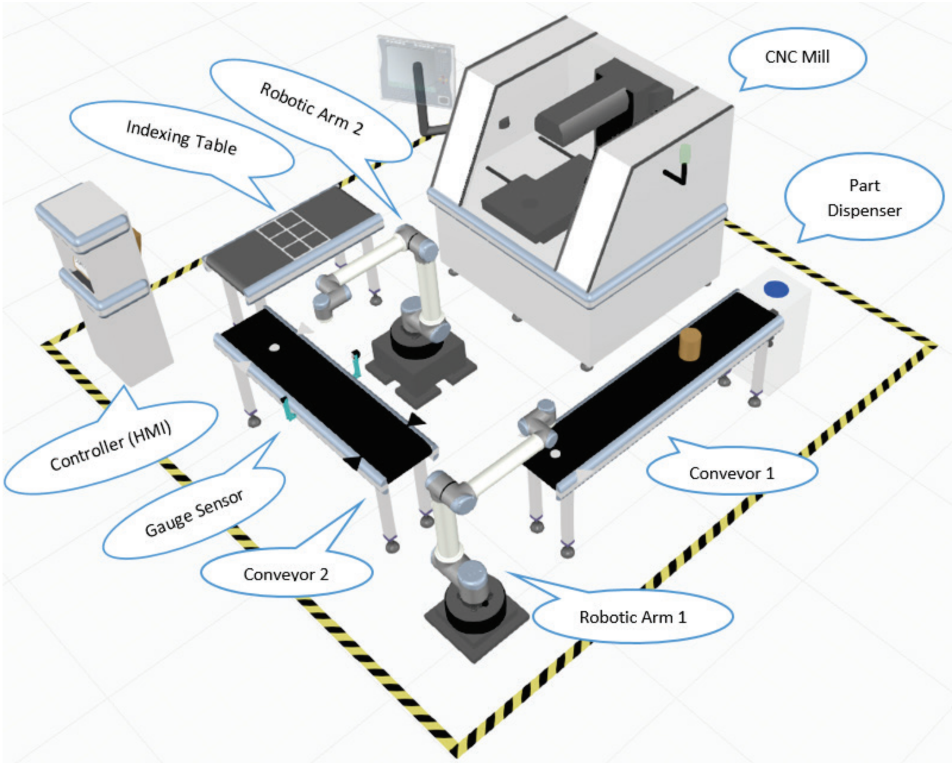


Figure 3.15a Layout and components of production system 1 (Created on: Visual Components 4.1)

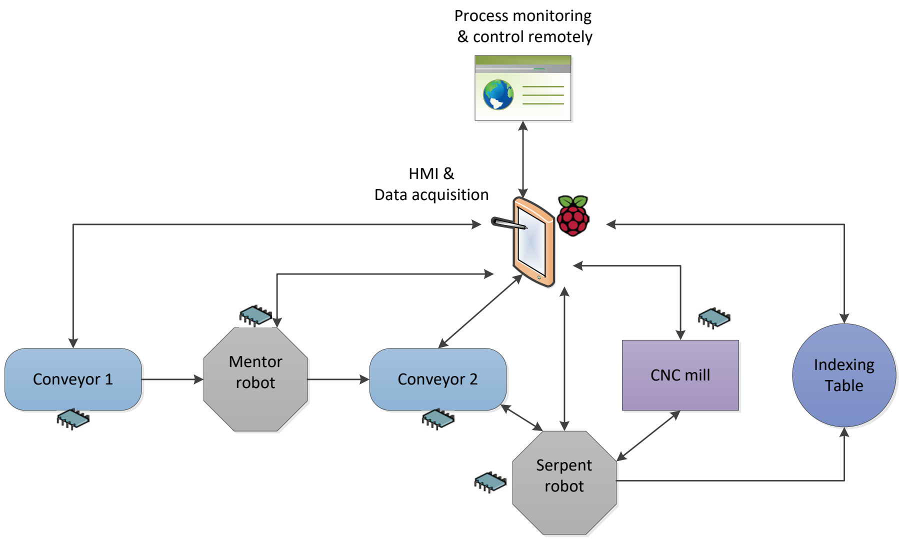


Figure 3.15b control architecture of the production system 1

Working Principle of Production System 2

The system starts with the pallets being stored into an Automated Storage and Retrieval System (ASRS) rack. As soon as the pallets available in the rack the system start retrieving pallets automatically, a pallet moves to drilling station via conveyor and drilling has performed. After drilling the pallet reaches to an assembly station where a robot adds components to the pallet and made the product ready. Followed by an inspection (checking) activity by a camera or sensor. At the end of the assembled (finished) product stored again into the ASRS rack. The whole process is automatic, but the system needs human assistance for setup the ASRS rack, taking the finished part of the rack and filling the inventory at the assembly station.

Figure 3.16a Production system 2

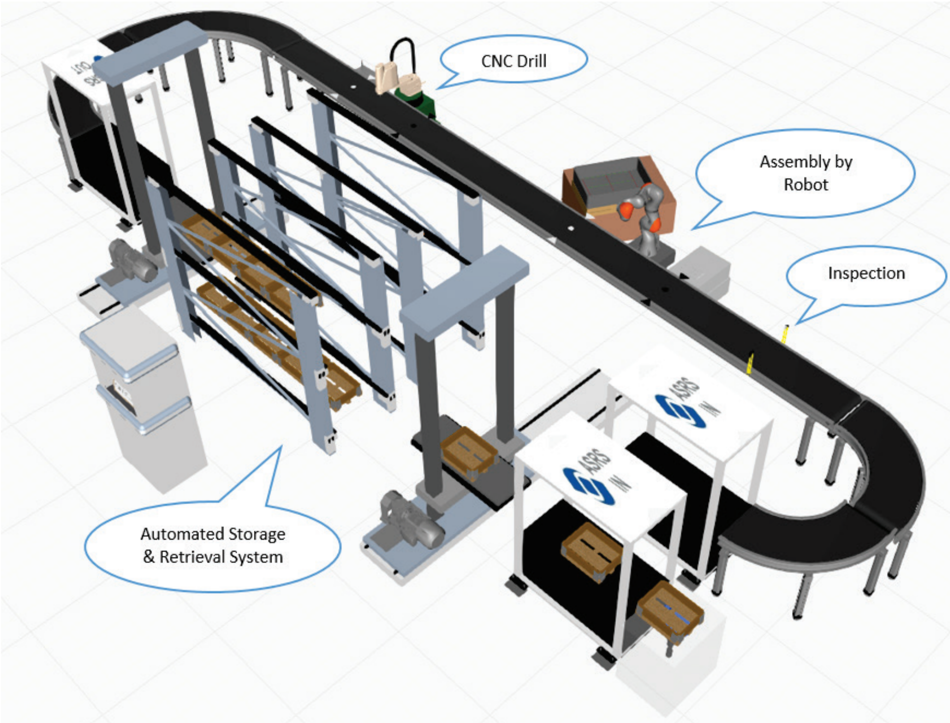


Figure 3.16b Layout and components of production system 2 (Created on: Visual Components 4.1)

Following is the step-by-step implementation of the performance evaluation concept (detailed description is provided in the *Paper V*):

Realise & Define System – Two automated production systems (lines) were considered for implementation and described their position in a VE.

Selection of KPIs – Throughput, OEE and Utilization were selected to estimate the productivity and effectiveness of the production systems (based on Fig. 3.12).

Process Modelling – The sequence of the process steps, including input and outputs are modelled of both production systems through EPC process modelling.

Data Collection – The collection of data from the databases of the production systems were done through generating queries. The communication between systems and IoT platform was executed by an application programming interface (API).

Real-time Visualization – A dashboard was developed with the help of a commercial IoT platform (Wapice IoT-TICKET) to monitor and visualise the selected KPIs for the FESTO production system as depicted in Fig. 3.17.

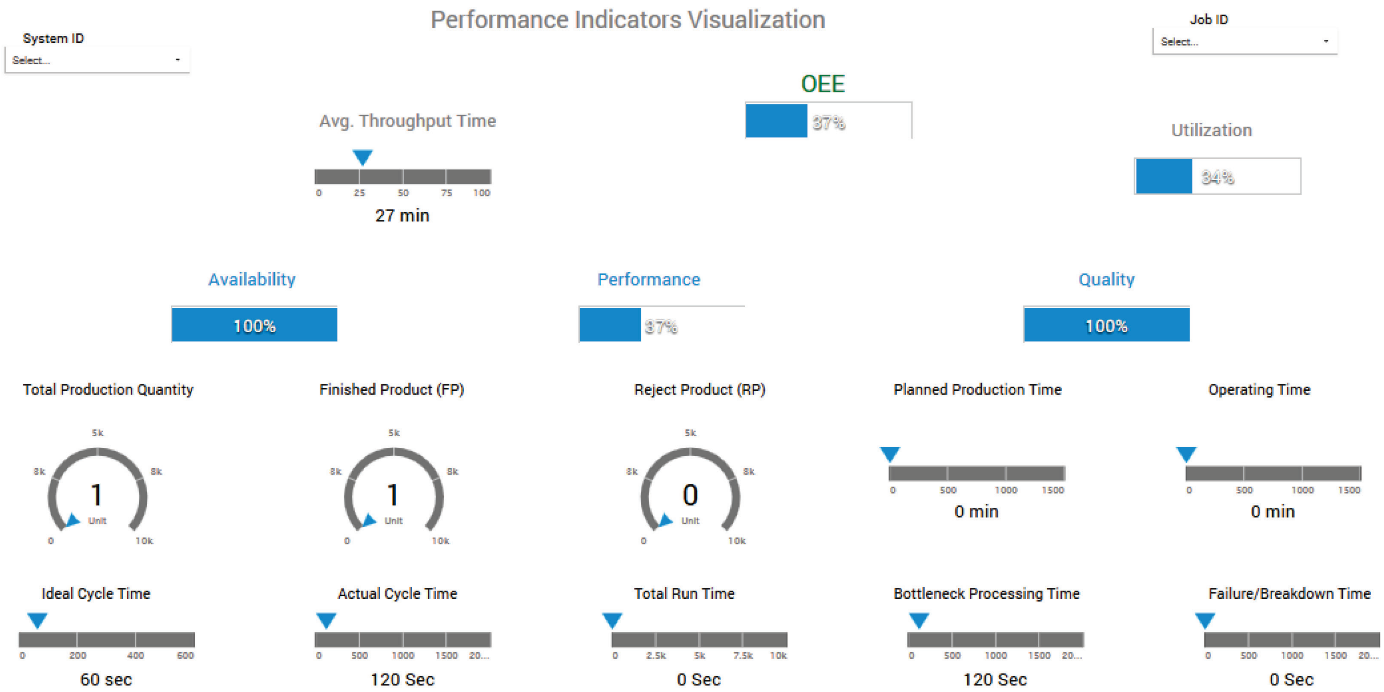


Figure 3.17 Dashboard for KPIs visualisation of a production system (Created on: IoT-TICKET) [V]

With the help of comparison matrix, initial opinions gather based on the questionnaire for SMEs and academic researchers, the weights of objective functions are estimated. As shown in the tables 3.7 and 3.8.

Table 3.7 Comparison matrix of KPIs

Comparison Matrix	**Throughput (ER1.1)**	**OEE (ER1.2)**	**Utilisation (ER1.3)**
Throughput (ER1.1)	-	ER1.1	ER1.1
OEE (ER1.2)	-	-	ER1.2
Utilization (ER1.3)	-	-	-

Table 3.8 Weight of KPIs by the pairwise ranking tactic

KPI	**Rank**	**Weight**
ER1.1	1st	0.67
ER1.2	2nd	0.33
ER1.3	3rd	0.00

The observed values of KPIs are normalised with the help of equation 3.4 and summarized in table 3.9.

Table 3.9 Normalized value of KPIs

KPIs	**Max. value**	**Min. value**	**Avg. value**	**Norm. value**
Throughput (units/hrs.)	2.0	1.0	1.5	0.5
OEE (%)	80	37	60	0.53
Utilization (%)	75	34	55	0.51

By using equation 3.5, the P_S factor for the case production system can be estimated as:

$$P_s = (0.67 \times 0.5) + (0.33 \times 0.53) + (0.00 \times 0.51) = 0.50$$

Hence, the P_S factor of the studied system was 0.50 on the scale 0 to 1. Where *0* is minimum and *1* is maximum.

4. Discussion, Conclusions and Further Work

The proposed reliability approach was validated through the case studies. The reliability factor of a virtual enterprise V_R is the combination of R_Z and P_S as defined in equation (1). For the optimal reliability, the R_Z value should be as minimum and the P_S value should be as maximum as possible within the described ranges. Based on the particular case studies the V_R can be seen as {3, 0.5}, which means the risk of a virtual enterprise was within the minimum range and performance of a production system was found out as average.

The implementation of risk assessment concept for a VE requires the periodic information about the frequency of risk events from each player of a VE, which should store to cloud-based storage. This information should be transformed into the evaluation matrix to perceive the risk profile associated with the VE of SMEs. Furthermore, it would help to set-up and adjust the risk management strategy and tactics. Therefore, the concept of risk assessment proactively contributes to the reliability of a VE. On the other hand, the performance evaluation concept for production systems with the help of identified KPIs enabled the visualisation of individual production systems status in the network. By using this information, the proactive decision making and control of production flow can be improved within the VE of SMEs.

The proposed approach contributes as a comprehensive model of the existence of a virtual enterprise with its risk assessment that is unique itself. This preventive approach gives a value to the decision makers about the reliability of a business opportunity. The research also targets a synchronised way to assess the performance of production systems or production lines and real-time visualisation, which helps SMEs to collaborate efficiently and maintain competitiveness. Moreover, the new possibilities of information sharing, data gathering platforms and communication interfaces in manufacturing environments with the help of industrial internet technologies are used in the approach. The integration of IIoT to the defined methods resulted in a new concept of performance evaluation of production systems in a SMEs network.

The substantial outcomes accomplished in this doctoral research consist of both the theoretical and practical implications. The innovations expand the theoretical background in the field of production engineering and its application, for example, to improve the course of information systems for production management and digital manufacturing. The practical importance of the research lies with the companies who are willing to collaborate effectively and to be reliable towards a business opportunity, especially the SMEs in the manufacturing domain. The evaluation approach of a VE elaborated during the PhD research can be taken as an input for an IT program development to assess and monitor the production systems in a VE of SMEs.

Following are the general conclusions of this research work based on the objectives and results acquired.

1) The proposed reliability management approach enables to evaluate the VE reliability based on the identified risks and their assessment; it also facilitates the analysis of production systems vulnerability based on the key performance indicators. The developed concepts can be applied as a preventive approach, which helps decision makers (stakeholders) to manage and improve the reliability of a VE. Additionally, it would enhance the collaboration between SMEs to share their resources and be competitive in a dynamic manufacturing environment in order to earn value from a business opportunity.

2) To enhance the reliability, the developed concept of risk assessment for the lifespan of a VE supports decision-makers of SMEs network to frame and estimate the potential risks and to establish an action plan for the mitigation of the overall virtual enterprise risk.
3) The developed performance evaluation concept for production systems in a virtual enterprise of SMEs with a tested case resulted in the contribution to how the performance evaluation of production systems should be conducted in a harmonised way and how it may visualise in a network with the help of industrial internet of things.

Future work:

- The proposed approach can be developed further by introducing more possible risks in the risk assessment concept for a virtual enterprise and by applying the concept to different case studies to get feedback for continuous improvement. Moreover, the advancement in risk mitigation strategies with the help of new industrial technologies such as IoT enabled framework can be a future development.
- The currently proposed concept of performance evaluation for production systems can also be extended in future by tested in with more case studies and enrich it with the inclusion of additional key performance indicators. Which can be integrated with the information system of enterprises.

References

[1] I. Polyantchikov, E. Shevtshenko, T. Karaulova, T. Kangilaski and L. M. Camarinha-Matos, “Virtual enterprise formation in the context of a sustainable,” *Industrial Management & Data Systems,* vol. 117, no. 7, pp. 1446-1468, 2017.

[2] P. Bouwen, “Corporate lobbying in the European Union: the logic of access,” *Journal of European Public Policy,* vol. 9, no. 3, p. 365-390, 2002.

[3] P. Bouwen, “The Logic of Access to the European Parliament: Business Lobbying in the Committee on Economic and Monetary Affairs,” *Journal of Common Market Studies,* vol. 42, no. 3, pp. 473-495, 2004.

[4] P. Markussen and G. T. Svendsen, “Industry lobbying and the political economy of GHG trade in the European Union,” *Energy Policy,* vol. 33, no. 2, pp. 245-255, 2005.

[5] Eurostat European Commission, “Key figures on European business with a special feature on SMEs,” Publications Office of the European Union, Belgium, 2011.

[6] OECD Policy Briefs, “Small and medium-sized enterprises: local strength, global reach.,” Public Affairs Division, OECD, 2000.

[7] European Commission, “User guide to the SME Definition,” Publications Office of the European Union, Luxembourg, 2015.

[8] E. P. S. Rojas, A. C. Barros, A. L. d. Azevedo and A. Batocchio, “Business model development for virtual enterprises,” in *PRO-VE, IFIP*, London, 2012.

[9] J. S. Oakland, Total Quality Management and Operational Excellence, New York: Routledge, 2014.

[10] British Standards (BS) 4778, “Quality vocabulary. Availability, reliability and maintainability terms. Guide to concepts and related definitions.,” British Standards Institution, London, 2017.

[11] M. Kostina, T. Karaulova, J. Sahno and M. Maleki, “Reliability estimation for manufacturing processes,” *Journal of Achievements in Materials and Manufacturing Engineering (AMME),* vol. 51, no. 1, pp. 7-13, 2012.

[12] A. Birolini, Reliability Engineering: Theory and practice, Berlin Heidelberg: Springer, 2007.

[13] P. O’Connor and A. Kleyner, Practical Reliability Engineering, West Sussex - UK: John Wiley & Sons, Ltd, 2012.

[14] J. Byrne, “The virtual corporation,” *Business Week,* pp. 98-102, 8 February 1993.

[15] L. M. Camarinha-Matos and H. Afsarmanesh, “Collaborative networks: a new scientific discipline,” *Journal of Intelligent Manufacturing,* vol. 16, no. 4-5, pp. 439-452, 2005.

[16] A. Lockamy and K. Mccormack, “Modeling supplier risks using Bayesian networks,” *Industrial Management & Data Systems,* vol. 112, no. 2, pp. 313-333, 2012.

[17] P. Hopkin, Fundamentals of Risk Management, London: Kogan Page, 2014.

[18] ISO 31000, “Risk Management,” International Organization for Standardization, Geneva, 2018.

[19] IRM, “Institute of Risk Management,” IRM, [Online]. Available: https://www.theirm.org/. [Accessed March 2018].

[20] SRA , “Society for Risk Analysis,” SRA, [Online]. Available: http://www.sra.org/. [Accessed March 2018].

[21] IIA, “The Institute of Internal Auditors,” IIA Global, [Online]. Available: https://global.theiia.org/Pages/globaliiaHome.aspx. [Accessed March 2018].

[22] PMI Standards , Project Management Body of Knowledge (PMBOK Guide), Pennsylvania: PMI, 2013.

[23] D. J. Smith, Realiability maintainability and risk - practical methods for engineers including reliability centred maintenance and safety-related systems, Oxford: Elsevier Butterworth-Heinemann, 2005.

[24] S. Gadd, D. Keeley and H. Balmforth, “Good practice and pitfalls in risk assessment,” Health and Safety Executive (HSE), Sheffield, 2003.

[25] A. Birolini, Reliability Engineering - Theory and Practice, Berlin: Springer, 2014.

[26] M. Rausand and A. Hoyland, System Reliability Theory: Models, Statistical Methods, and Applications, New Jersey: John Wiley & Sons, 2004.

[27] T. V. Stren, Lean Six Sigma - international standards and global guidelines, New York: CRC Press - Taylor & Francis Group, 2016.

[28] I. Cabral , A. Grilo and V. Cruz-Machado, “A decision making model for Lean, Agile, Resilient and Green supply chain management,” *International Journal of Production Research,* vol. 50, no. 17, pp. 4830-4845, 2012.

[29] P. Puvanasvaran, H. Megat, T. Hong, M. Razali and S. Abdel Magid, “Lean process management implementation through enhanced problem solving capabilities,” *Journal of Industrial Engineering and Management,* vol. 3, no. 3, pp. 447-493, 2010.

[30] Y. Monden, Toyota Production System: An Integrated Approach to Just-In-Time, Productivity Press, 2011.

[31] T. Ohno, Toyota Production System: Beyond large-scale production, Portland: Productivity press, 1998.

[32] J. Liker , The Toyota Way, New York: McGraw-Hill, 2004.

[33] Q. Brook, Lean six sigma and minitab - The complete toolbox guide for all lean six sigma practitioners, UK: OPEX Resources, 2014.

[34] P. L. King and J. S. King, Value Stream Mapping for the Process Industries - Creating a Roadmap for Lean Transformation, New York: Productivity Press, 2015.

[35] R. Basu, Implementing six sigma and lean - a practical guide to tools and techniques, London: Routledge, 2015.

[36] G. Issar and L. R. Navon, Operational Excellence - a concise guide to basic concepts and their application, Switzerland: Springer, 2016.

[37] T. Altiok, Performance Analysis of Manufacturing Systems - Springer Series in Operations Research and Financial Engineering, New York: Springer, 2012.

[38] R. Anupindi, S. Chopra , S. Deshmukh , J. Van Mieghem and E. Zemel, Managing Business Process Flows, Essex: Pearson Education, 2012.

[39] Supply Chain Council, Supply Chain Operations Reference Model (SCOR) REV. 11, USA: The Supply Chain Reference, 2012.

[40] M. Lanz, E. Järvenpää, H. Nylund, R. Tuokko, S. Torvinen and K. Georgoulias, “Sustainability and Performance Indicators Landscape,” in *Flexible Automation and Intelligent Manufacturing, FAIM*, Texas US, 2014.

[41] E. Järvenpää, H. Tokola, T. Salonen, M. Lanz, M. Koho and R. Tuokko, “Requirements for Manufacturing Operations Management and Control Systems in a Dynamic Environment,” in *Flexible Automation and Intelligent Manufacturing, FAIM*, Texas, US, 2014.

[42] H. Tokola, E. Järvenpää, T. Salonen, M. Lanz, M. Koho and E. Niemi, “SHOP FLOOR-LEVEL CONTROL OF MANUFACTURING COMPANIES: AN INTERVIEW STUDY IN FINLAND,” *Management and Production Engineering Review,* vol. 6, no. 1, pp. 51-58, 2015.

[43] S. Kaganski, J. Majak, K. Karjust and S. Toompalu, “Implementation of key performance indicators selection model as part of the Enterprise Analysis Model,” *Procedia CIRP,* vol. 63, no. 1, pp. 283-288, 2017.

[44] S. Kaganski, “Development and Implementation of the Key Performance Indicator Selection Model for SMEs,” TTÜ Press, Tallinn, 2018.

[45] R. Singh, D. Shah, A. Gohil and H. Shah, “Overall equipment effectiveness (OEE) calculation – Automation through hardware & software development,” *Procedia Engineering,* vol. 51, no. 1, pp. 579-584, 2013.

[46] A. Zuashkiani, H. Rahmandad and A. K. Jardine, “Mapping the dynamics of overall equipment effectiveness to enhance asset management practices,” *Journal of Quality in Maintenance,* vol. 17, no. 1, pp. 74-92, 2011.

[47] S. Nakajima, Introduction to Total Productive Maintenance (TPM), Cambridge. MA: Productivity Press, 1988.

[48] P. Muchiri and L. Pintelon, “Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion,” *International Journal of Production Research,* vol. 46, no. 13, pp. 3517-3535, 2008.

[49] S. Nakajima, TPM Development Program, Cambridge. MA: Productivity Press, 1989.

[50] J. Garza-Reyes, S. Eldridge, K. Barber and S. Meier, “Overall equipment effectiveness and process capability measures,” *International Journal of Quality & Reliability Management,* vol. 27, no. 1, pp. 48-62, 2008.

[51] C. Andersson and M. Bellgran, “On the complexity of using performance measures: Enhancing sustained production improvement capability by combining OEE and productivity,” *Journal of Manufacturing Systems,* vol. 35, no. 1, pp. 144-154, 2015.

[52] V. Bashkite and T. Karaulova, “Decision-making Framework for Used Industrial Equipment,” *Engineering Economics,* vol. 27, no. 1, pp. 23-31, 2016.

[53] W. Hopp and M. Spearman, Factory Physics, waveland press, 2011.

[54] J. Heizer and B. Render, Operations Management, Pearson Education, 2014.

[55] R. G. Askin and J. B. Goldberg, Design and Analysis of Lean Production Systems, USA: John Wiley & Sons, 2002.

[56] M. Laguna and J. Marklund, Business process modeling, simulation and design, CRC Press, 2013.

[57] M. Weske , Business Process Management - Concept, Languages, Architectures, Springer, 2012.

[58] D. Draheim, Business Process Technology - A unified view on business processes, workflows and enterprise application, Springer, 2010.

[59] IDEF, "Integrated DEFinition Methods (IDEF)," Knowledge Based Systems, [Online]. Available: http://www.idef.com/. [Accessed May 2018].

[60] Z. Bi, L. D. Xu and C. Wang, "Internet of Things for Enterprise Systems of Modern Manufacturing," *IEEE Transactions on Industrial Informatics,* vol. 10, no. 2, pp. 1537-1546, 2014.

[61] German innovation center for industry 4.0, "The Industry 4.0 Portal," [Online]. Available: https://i40.de/en/german-innovation-centre-for-industry-4-0-announces-the-digitalisation-and-industry-4-0-driver-licence/. [Accessed April 2018].

[62] D. Mourtzis, E. Vlachou and N. Milas, "Industrial Big Data as a result of IoT adoption in Manufacturing," *Procedia CIRP,* vol. 55, no. 1, p. 290–295, 2016.

[63] L. Monostori , "Cyber-physical production systems: Roots, expectations and R&D challenges," *Procedia CIRP,* vol. 17, no. 1, pp. 9-13, 2014.

[64] S. YIN and O. KAYNAK, "Big Data for Modern Industry: Challenges and Trends," *Proceedings of the IEEE ,* vol. 103, no. 2, pp. 143-146, 2015.

[65] i-Scoop, "Industry 4.0: the fourth industrial revolution – guide to Industrie 4.0," [Online]. Available: https://www.i-scoop.eu/industry-4-0/#Industry_40_is_not_just_about_factories_anymore. [Accessed April 2018].

[66] Siemens Product Lifecycle Management Software, "Siemens PLM - Digital Manufacturing," Siemens, [Online]. Available: https://www.plm.automation.siemens.com/global/en/our-story/glossary/digital-manufacturing/13157. [Accessed April 2018].

[67] T. Tolio, M. Sacco, W. Terkaj and M. Urgo, "Virtual Factory: an Integrated Framework for Manufacturing Systems Design and Analysis," *Procedia CIRP,* vol. 7, pp. 25-30, 2013.

[68] National Institute of Standards and Technology (NIST), "CYBER-PHYSICAL SYSTEMS," NIST Engineering Laboratory, [Online]. Available: https://www.nist.gov/el/cyber-physical-systems. [Accessed April 2018].

[69] J. Lee, B. Bagheri and H.-A. Kao, "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems," *Manufacturing Letters,* vol. 3, pp. 18-23, 2015.

[70] E. A. Lee and . S. A. Seshia, Introduction to embedded systems: A cyber-physical systems approach, London: The MIT Press, 2017.

[71] H. Tokola, C. Gröger, E. Järvenpää and E. Niemi, "Designing manufacturing dashboards on the basis of a Key Performance Indicator survey," *Procedia CIRP,* vol. 57, no. 1, pp. 619-624, 2016.

[72] D. Kolberg and D. Zuhlke, "Lean Automation enabled by Industry 4.0 Technologies," *IFAC-PapersOnLine,* vol. 48, no. 3, pp. 1870-1875, 2015.

[73] T. Wagner , C. Herrmann and S. Thiede, "Industry 4.0 impacts on lean production systems," *Procedia CIRP,* vol. 63, no. 1, pp. 125-131, 2017.

[74] B. Mrugalska and M. K. Wyrwicka , "Towards Lean Production in Industry 4.0," *Procedia Engineering,* vol. 182, p. 466-473, 2017.

[75] L. Camarinha-Matos and H. Afsarmanesh, “Classes of collaborative networks,” in *Encyclopedia of Networked and Virtual Organizations*, IGI Global, 2008.

[76] B. Knoke and J. Eschenbächer, “Virtual Enterprise Environments (VEEs) to Enable Innovation in Collaborative Networks – Initial Modelling Approach,” in *Collaborative Networks in the Internet of Services*, Bournemouth, UK, Springer, 2012, pp. 616-623.

[77] J. Ziegler, R. Buchmann, M. Graube, J. Hladik, T. Münch, P. Ortiz, J. Pfeffer, F. Schneider, M. Uriarte, D. Karagiannis and L. Urbas, “Implementation and Operation of Collaborative Manufacturing Networks,” in *Collaborative Systems for Smart Networked Environments*, Amsterdam, The Netherlands, Springer, 2014, pp. 197-208.

[78] V. Modrak and S. Bednar, “Complexity Mitigation in Collaborative Manufacturing Chains,” in *Collaboration in a Hyperconnected World*, Porto, Portugal, Springer, 2016, pp. 411-419.

[79] G. Liu, X. Zhou, J. Zhang and W. Zhang, “Risk assessment of virtual enterprise based on the fuzzy comprehensive evaluation method,” in *Integration and Innovation Orient to E-Society - IFIP*, Wuhan, China, Springer, 2007, p. 58-66.

[80] M. Huang, L. Fu-Qiang, W.-K. Ching and T. K. Siu, “A distributed decision making model for risk management of virtual enterprise,” *Expert Systems with Applications,* vol. 38, p. 13208-13215, 2011.

[81] O. C. Alves Junior, R. J. Rabelo, R. G. Vieira and A. Fiorese, “A Risk Analysis Method for Selecting Logistic Partners to Compose Virtual Organizations,” in *Collaborative Systems for Reindustrialization*, Dresden, Germany, Springer, 2013, pp. 527-539.

[82] J. Rosas, P. Macedo, A. Tenera, A. Abreu and P. Urze, “Risk Assessment in Open Innovation Networks,” in *Risks and Resilience of Collaborative Networks*, Albi, France, Springer, 2015, pp. 27-38.

Acknowledgements

The work presented in this dissertation was conducted at the Department of Mechanical and Industrial Engineering, School of Engineering, Tallinn University of Technology.

Firstly, I would like to thank and express my immense gratitude to my supervisors, Professor Tauno Otto and Associate Professor Eduard Ševtšenko for their relevant assistance, guidance and encouragement. I would also like to thank all the other co-authors and staff of FMS and Robotics DemoCentre at TalTech. Secondly, I wish to thank all the staff at the Laboratory of Mechanical Engineering and Industrial Systems at Tampere University of Technology, especially Prof. Minna Lanz and Assoc. Prof. Andrei Lobov for help in conducting experiments.

Finally, I wish to pay my warm regards and gratefulness to my family that support me during the studies and research.

The work was supported by:

- Project AR16077 Smart Industry Centre (SmartIC) No. 2014-2020.4.01.16-0183, supported by the EU Regional Development Fund.
- Project: B41 – Collaboration enhancing sustainable conceptual model development and implementation for the SME-s in machinery domain.
- Innovative Manufacturing Engineering Systems Competence Centre IMECC (supported by Enterprise Estonia and co-financed by European Union Regional Development Fund, project EU48685).

Abstract

Reliability Management Approach for a Virtual Enterprise of SMEs in a Manufacturing Domain

Due to the rapid evolvement of industrial technologies, manufacturing companies are facing challenges to carrying all the necessary competence of business processes to fulfil the customer demands. Meanwhile, companies are more focusing in their particular fields. Therefore, it is tough to own all the necessary technologies and expertise in a house, especially for SMEs. SMEs are often reacted on those challenges by establishing a network and it can be in a form of Virtual Enterprise (VE) to share the resources.

However, the virtual enterprise is exposed to the certain risks and leads to reliability management issues during its working cycle as the resources such as production systems are shared. Moreover, the performance of production systems which are located in a virtual enterprise are need to be addressed and should be evaluated, in order to fulfil the business opportunity and helps in proactive decision making. Recent emergence of new technologies in the manufacturing domain like Industrial Internet of Things etc. combined with the existing methods can be useful to mitigate the reliability issues of a virtual enterprise of SMEs as it may achieve by getting insight about the ongoing activities at the factory floor where production systems are placed. *The integration of risk assessment process combined with an IoT-based concept of production systems evaluation module into the virtual enterprise model is a main output of the dissertation.*

The reliability management approach for the virtual enterprise of SMEs would help decision-makers of a collaborative network of SMEs to formulate and estimate the potential risks and to set up an action plan to mitigate the overall virtual enterprise risks, which also supports to improve their business model reliability. Moreover, it facilitates to how the performance evaluation of production systems should be conducted in a harmonized way and how it may visualize in a network with the help of industrial internet of things. Which leads to enhance the collaboration among SMEs, share their resources and be competitive, hence, capable to earn value from business opportunity. The objective of this thesis is to develop an approach to assess the risks of a VE and to evaluate the performance of production systems in a VE of SMEs. The approach consists of two concepts, first concept is to analysing the key risk factors and to assess the level of risk a VE faces during its whole functioning period and steps are as follows:

- Defining the phases of existence of a VE through the process modelling activity
- Risks identification and classification by the brainstorming activity
- Estimation and evaluation of risks with the help of risk matrix
- Determination of overall risk level of a VE through the Fault Tree Analysis
- Improvement and monitoring using IIoT concept

Second concept is about the performance evaluation of production systems in an SME network with the adoption of Internet of Things (IoT) in manufacturing and comprises of following steps:

- Realize and Define System (description of VE)
- Selection of KPIs for production systems
- Process modelling of different levels (shop floor to enterprise level)
- Data collection by industrial internet of things technologies
- Monitoring & Visualization (Real time) through a dashboard

The whole reliability management process has been described and its relevance was validated through case studies. Since the situation of studied cases are changed dynamically due to the advancement of technologies and with individual specifics, hence the approach can be executed continuously.

All in all, the execution of risk assessment concept for a VE needs the periodic information about the frequency of risk events from each actor of a VE, which should be stored to cloud-based storage. This information should be transformed into the evaluation matrix to perceive the risk profile associated to the VE of SMEs. Furthermore, it would help to set-up and adjust the risk management strategy and tactics. Therefore, the concept of risk assessment proactively contributes for the reliability of a VE. On the other hand, the performance evaluation concept for production systems with the help of identified KPIs enabled the visualization of individual production systems status in the network. By using this information, the proactive decision making and control of production flow can be improved within the VE of SMEs.

The proposed approach contributes as a comprehensive model of the existence of a virtual enterprise with its risk assessment that is unique itself. This preventive approach gives a value to the decision makers about the reliability of a business opportunity. The research also targets a synchronized way to assess the performance of production systems or production lines and real-time visualization, which helps SMEs to collaborate efficiently and maintain competitiveness. Moreover, the new possibilities of information sharing, data gathering platforms and communication interfaces in the manufacturing environments with the help of industrial internet technologies are used in the approach. The integration of IIoT to the defined methods resulted in a new concept of performance evaluation of production systems in a SMEs network.

Lühikokkuvõte
Usaldusväärsuse juhtimise raamistik tootmis valdkonna väikese ja keskmise suurusega virtuaalettevõtetele

Tänu tööstustehnoloogia kiirele arengule, seisavad tootmisettevõtted silmitsi väljakutsega olla kõikides äriprotsessides pädevad täitmaks kliendi nõudeid. Samal ajal on ettevõtted üha rohkem keskendunud oma konkreetsetele valdkondadele. Seetõttu on eriti väikeste ja keskmise suurusega ettevõtete jaoks raske evida kõiki vajalikke tehnoloogiaid ja teadmisi. Väikesed ja keskmise suurusega ettevõtted reageerivad sageli nendele väljakutsetele võrgustiku loomise kaudu, mis võib olla ressursside jagamiseks virtuaalettevõtte (VE) kujul.

Kuid virtuaalettevõte on avatud reale ohtudele ja see viib tööprotsessis juhtimise usaldusväärsuse probleemidesse, sest olulised ressursid nagu tootmissüsteemid on jagatud. Peale selle tuleb virtuaalettevõttes asuvate tootmissüsteemide toimivust käsitleda ja hinnata, et ärivõimalusi paremini kasutada ja aidata kaasa proaktiivsete otsuste tegemisele. Uute tootmisvaldkonda jõudnud läbimurdetehnoloogiatest, näiteks tööstuslik asjade internet jne integreerimine väljatöötatud meetoditega võib olla kasulik VKEde virtuaalettevõtte usaldusväärsuse probleemide leevendamiseks, kuna see võimalab saada parema ülevaate käimasolevate tegevuste kohta tsehhis asuvatest tootmissüsteemidest.

VKEde virtuaalettevõtte usaldusväärsuse juhtimise lähenemisviis aitaks VKEde koostöövõrgustiku otsustajatele kujundada ja hinnata võimalikke ohte ja luua tegevuskava üldiste virtuaalsete ettevõtlusriskide leevendamiseks, mis toetab ka nende äritegevuse parandamist mudeli usaldusväärsus. Lisaks hõlbustab see tööstusliku asjade interneti abil tootmissüsteemide toimivuse hindamise harmoniseerimist ja võrgustikus visualiseerimist. See suurendab väikeste ja keskmise suurusega ettevõtete vahelist koostööd, aitab jagada nende tootmisressursse ja on konkurentsivõimeline, seega suudab teenida kasu ärivõimalustest. Selle väitekirja eesmärgiks oli välja töötada metoodika virtuaalettevõtte riskide hindamiseks ja väikeste ja keskmise suurusega ettevõtete tootmissüsteemide toimivuse hindamiseks.

Metoodika hõlmab kahte meetodit, kusjuures esimene meetod võimaldab analüüsida peamisi riskitegureid ja hinnata riski taset, mida virtuaalettevõte kogu oma toimimisperioodi vältel kokku puutub. Selle ja sammud on järgmised:

- VE-i olemasolu faaside määratlemine modelleerimisprotsessi abil
- Riskide tuvastamine ja liigitamine ajurünnakute abil
- Riski hindamine ja hindamine riskimaatriksi abil
- VE-i üldise riskitaseme kindlaksmääramine vigade puu analüüsi kaudu
- Parandamine ja järelevalve kasutades IIoT tehnoloogiat

Teine meetod puudutab tootmissüsteemide toimivuse hindamist VKEde võrgustikus, kus aset leiab tööstusliku asjade interneti (IIoT) ja mis koosneb järgmistest etappidest:

- Süsteemi realiseerimine ja defineerimine (VE-kirjeldus)
- KPIde valimine tootmissüsteemide jaoks
- Erinevate tasandite protsesside modelleerimine (tsehhi tasandist ettevõtete tasandini)
- Andmete kogumine tööstusliku asjade interneti kaudu
- Seire ja visualiseerimine (reaalajas) juhtpaneeli kaudu

Kogu usaldusväärsuse juhtimise protsess ja selle asjakohasus on valideeritud juhtumiuuringute abil. Kuna uuritud juhtumite olukord muutub dünaamiliselt tehnoloogiate arendamise ja individuaalsete eripärade tõttu, tuleb seda metoodikat kasutada pidevalt.

Kokkuvõttes vajab VE riskianalüüsi teostamise kontseptsioon korrapäraselt teavet VE iga osaleja riskide sageduse kohta, mida kasutatakse pilvepõhiseks ladustamiseks. See teave transformeeritakse hindamismaatriksiks, et VKE-dega seotud riskiprofiile määrata. Lisaks aitaks see kaasa riskijuhtimise strateegia ja taktikate seadistamisele ja korrigeerimisele. Seetõttu aitab riskihindamise kontseptsioon ennetavalt VE-i usaldusväärsust. Teisest küljest võimaldas tootmissüsteemide tulemuslikkuse hindamise kontseptsioon tuvastatud KPIde abil kaasa individuaalsete tootmissüsteemide staatuse visualiseerimisele võrgus. Selle teabe abil saab VKEde VKE-s suurendada ennetavat otsustusprotsessi ja kontrollida tootmisvoogu.

Pakutud lahendus loob virtuaalettevõtte tervikmudeli, mida ersitab varasematest riskianalüüsi komponendi sissetoomine. See ennetav lähenemisviis loob ärivõimaluste usaldusväärsuse hindamismetoodika abil otsustajatele lisandväärtust. Uurimistöös on uuritud ka tootmissüsteemide või tootmisliinide toimivuse ja reaalajas visualiseerimise sünkroniseerimisest, mis aitab VKEdel tõhusalt koostööd teha ja konkurentsivõimet säilitada. Loodud metoodikas kasutatakse ka tootmiskeskkonnas tööstusliku asjade interneti tehnoloogia abil infojagamise, ja andmekogumise platvormide ja kommunikatsiooniliideste uusi võimalusi. IIoT integreerimine võimaldas VKEde võrgustikus luua tootmissüsteemide tulemuslikkuse hindamise uue kontseptsiooni.

Appendix

Paper I

Mahmood, K.; Shevtshenko, E.; Karaulova, T.; Otto, T. (2018). Risk assessment approach for a virtual enterprise of small and medium-sized enterprises. *Proceedings of the Estonian Academy of Sciences*, 67 (1), 17−27. https://doi.org/10.3176/proc.2017.4.27

Paper II

Shevtshenko, E.; Poljantchikov, I.; **Mahmood, K**.; Kangilaski, T.; Norta, A. (2015). Collaborative Project Management Framework for Partner Network Initiation. *Procedia Engineering*, 100, 159−168. Proceedings of the 25th DAAAM International Symposium on Intelligent Manufacturing and Automation, Elsevier.
https://doi.org/10.1016/j.proeng.2015.01.354

Paper III

Mahmood, K.; Shevtshenko, E. (2015). Analysis of machine production processes by risk assessment approach. *Journal of Machine Engineering*, 15 (1), 112−124.

https://www.etis.ee/Portal/Publications/Display/f717f8e2-cb78-42df-bdb7-2d17a1861903

Paper IV

Mahmood, K.; Karaulova, T.; Otto, T.; Shevtshenko, E. (2017). Performance Analysis of a Flexible Manufacturing System (FMS). *Procedia CIRP*, 63, 424–429. Proceedings of the 50th CIRP CMS, Elsevier. https://doi.org/10.1016/j.procir.2017.03.123

Paper V

Mahmood, K.; Lanz, M.; Toivonen, V.; Otto, T. (2018). A Performance Evaluation Concept for Production Systems in an SME Network. *Procedia CIRP*, 72, 603–608. Proceedings of the 51st CIRP CMS, Elsevier. https://doi.org/10.1016/j.procir.2018.03.182

Curriculum vitae

Personal data

Name: Kashif Mahmood
Date of birth: 28.05.1986
Place of birth: Karachi
Citizenship: Pakistan

Contact data

E-mail: kashif_068@hotmail.com

Education

2014 –	Tallinn University of Technology – PhD
2013 – 2014	Linköping University – Exchange studies (MSc)
2012 – 2014	Tallinn University of Technology – MSc
2006 – 2010	NED University of Engineering and Technology – BE
2003 – 2005	D.J. Science College – Higher Secondary School

Language competence

English – Fluent
Urdu – Fluent
Estonian – Basic

Professional employment

2017 –	Tallinn University of Technology, Early Stage Researcher
2016 – 2017	Tampere University of Technology, Visiting Researcher
2015 – 2017	Tallinn University of Technology, Engineer
2010 – 2012	Tri-Pack Films Ltd. Pakistan, Production Planner

Elulookirjeldus

Isikuandmed

Nimi: Kashif Mahmood
Sünniaeg: 28.05.1986
Sünnikoht: Karachi
Kodakondsus: Pakistan

Kontaktandmed

E-post: kashif_068@hotmail.com

Hariduskäik

2014 –	Tallinna Tehnikaülikool – PhD
2013 – 2014	Linköping Ülikool – Vahetusuuringud (MSc)
2012 – 2014	Tallinna Tehnikaülikool – MSc
2006 – 2010	NED University of Engineering and Technology – BE
2003 – 2005	D.J. Science College – Higher Secondary School

Keelteoskus

Inglise keel – kõrgtase
Urdu – kõrgtase
Estonian – algtase

Teenistuskäik

2017 –	Tallinna Tehnikaülikool, Nooremteadur
2016 – 2017	Tampere Tehnikaülikool, Külalisteadur
2015 – 2017	Tallinna Tehnikaülikool, Insener
2010 – 2012	Tri-Pack Films Ltd. Pakistan, Tootmise planeerija