TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Mechanical and Industrial Engineering

IOT BASED FRAMEWORK FOR COMPRESSED AIR SYSTEM MANAGEMENT IN O-I PRODUCTION ESTONIA AS

IOT BAASIL PÕHINEV RAAMISTIK SURUÕHU SÜSTEEMIDE HALDAMISEKS O-I PRODUCTION ESTONIA AS'S

MASTER THESIS

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Tallinn, 2018

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Thesis is in accordance with terms and requirements

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Accepted for defence

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TUT Department of Mechanical and Industrial Engineering

THESIS TASK

Student: **Robert Jakobson**

Study programme: Industrial Engineering and Management

Supervisor: Eduard Ševtšenko - Associate Professor

Thesis topic:

(English) IoT based Framework for compressed air system management in O-I Production Estonia AS

(Estonian) IoT baasil põhinev raamistik suruõhu süsteemide haldamiseks O-I Production Estonia AS's

Thesis main objective:

To propose a framework for developing an IoT based system for compressed air system management in order to reduce uncertainties, plan preventive actions and to collect data for further improvements.

Thesis tasks and time schedule:

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PREFACE

Objective of the thesis is to develop an IoT based framework for compressed air management in O-I Production Estonia AS for preventive and improvement actions in the system. This thesis topic was initiated by the author and is related to authors everyday job profile as Maintenance Manager and Plant Engineer in O-I glass container production plant in Järvakandi. Necessary data for thesis was gathered internally from Järvakandi plant.

First and foremost, the author of the thesis would like to thank the Järvakandi previous plant manager Piotr Jakubazko for supporting this thesis framework deployment. Hereupon, without the guidance and perspicacity from Associate Professor Eduard Ševtšenko, this thesis would not be as it is today. Additionally, the author of the thesis would like to share appreciation to all contributors for this thesis from the plant, as they are: Vello Veinberg, Joonas Tiido, Tarmo Orav and Märt Kruusmaa.

LIST OF ABBREVIATIONS AND SYMBOLS

IoT – Internet of things

CPS – Cyber-Physical system

OEE – Overal Equipment Effectiveness

MTBF – Mean Time Between Failures

MTTF – Mean Time To Failure

MTTR – Mean Time To Repair

RP – Reliability Prediction

RBD - Reliability Block Diagram

FTA – Fault Tree Analysis

FMEA – Fault Mode and Effect Analysis

RPN – Risk Priority Number

LPS – Low Pressure System

HPS – High Pressure System

O-I – Owens Illinois

ROI – Return on Investment

1 INTRODUCTION

Over the last decade there has been several changes in glass container and packaging industry, were long planning and delivery times for simple designed mass production containers have changed to highly tailored design with small batches and with flexible fast delivery periods globally. To adapt with new market standards, to be more sustainable, this old industry needs to take over the new methodology of future industry as Industry 4.0. Which would help to gain efficiency not only in production area, but also raises equipment reliability, sustainability and what most important employee's safety at all levels.

The glass container manufacturing industry is a harsh and demanding due to its process peculiarities with enormous energy consumption and includes heat, vibration, radiation, noise. It needs 24/7 365 days and most of times up to 18 years in a row observation and support from all supportive structures to be sustainable. The type of glass furnaces used for container manufacturing industry and also here in Estonia at O-I are continuous and always *on type* which means, it needs constantly flowing through glass to be efficient. To fulfil this requirement, it is crucial to keep container forming machines and other continuous process steps always working. If we leave out electrical energy, there are couple of crucial supportive systems such as natural gas, oxygen, compressed air, vacuum and raw water. Simply shutting down one of previously mentioned support system will affect the whole flow and may cause chaos, in big picture, it is corporation goal to eliminate this kind of uncertainty. Today we can be experiencing sudden failures in the compressed air system, what is caused of lacking monitoring systems, and often it takes plant to standstill or cause some production losses. Additionally, we are often producing more compressed air than we need, due to no monitoring or regulating system prior the need and this is generally wasting energy and money.

Owens-Illinois is the only glass container manufacturer in Estonia who is focused to premium products, such as spirits and food containers from high quality flint glass. To fulfil previously mentioned market shifts over the decade, they have decided to adapt new industry standards to raise the efficacy and cut out unexpected interruptions/stops in production and its processes. They have built a corporation internal standard which is called GMF (Global Manufacturing Fundamental) which states how all processes internally have to operate and perform, also goes hand in hand with Industry 4.0 ideology. Second tool what is widely used in compliance with GMF is Lean Six Sigma, to eliminate waste and improve processes.

The main objective of this thesis is to propose a possible solution for continuous observation for critical support system as compressed air, by applying IoT, Industry 4.0 ideology, reliability engineering tools and Lean Six Sigma methodology. Main focus points for continuous observation are to:

- Downtime and cause registration
- Preventive maintenance planning
- Resource measuring and optimization
- Equipment lifecycle/health evaluation

Furthermore, previously mentioned data will help management to make decision on future investments, putting together maintenance budget, scheduling workforce and planning downtime on machines. Secondly, and the most important factor is reliability as safety gain.

The structure of the thesis is as follows. First chapter gives a through overview of used ideology's and methodologies in the thesis as they are basis for framework development and deployment. It includes Industry 4.0, IoT, Lean Six Sigma ideologies and Reliability engineering tools for improvement analyses. Chapter ends with selecting suitable reliability engineering tool for the framework development. As it follows, next chapter covers an IoT based framework development with step-by-step description how it can be used. Following chapter gives an overview of Järvakandi O-I plant and its production processes. In the first part of chapter, will be described how dependent is plant on compressed air. Chapter includes also compressed air system detailed description and current layout. Further on, FMEA analysis will be performed in sight of IoT system design. Chapter ends with developed IoT solution layout and payback calculations. Last chapter is about framework deployment in the plant, where first will be proven provided system feasibility and there on step-by-step implementation of designed system.

2 THEORY AND METHODS

In this chapter the author of the thesis will give an overview of Industry 4.0, IoT and Lean Six Sigma ideologies what are implemented together with one of the Reliability Engineering tool for building an IoT based infrastructure to monitor compressed air systems. Chapter covers also most widely used reliability engineering tools and ends with choosing the most suitable one for developing and IoT based management system.

2.1 Industry 4.0

It states to be high-tech project, started by the German government, who promotes the computerization of manufacturing. Before moving onto Industry 4.0, it would be beneficial to give short overview about what Industry 1.0, 2.0 & 3.0 were (Figure 2.1). The first industrial revolution was the mechanization of production using water and steam power. The second industrial revolution then introduced mass production with the help of electric power, followed by the third industrial revolution digital revolution and the use of electronics and IT to further automate production [1]. Now is already running Fourth industrial revolution as stated as Industry 4.0, which is coming from name “Industrie 4.0” what was initiated by the German government officials, industry leaders and academics at Hannover Messe in 2011 [2].

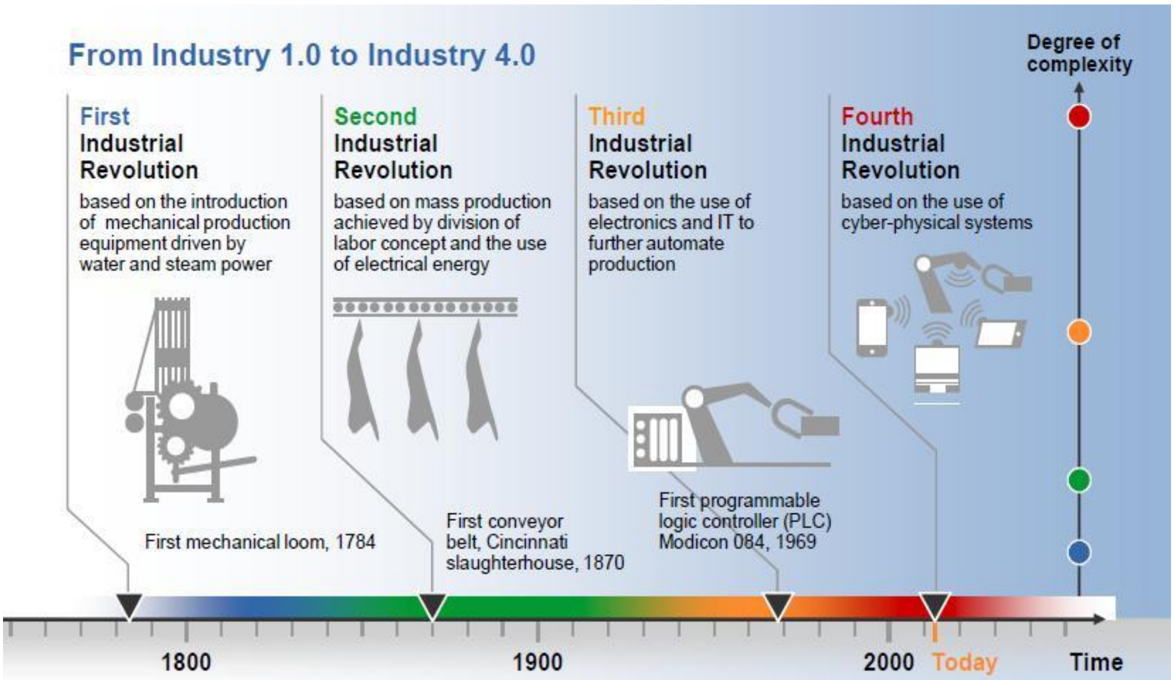

Figure 2.1 The four stages of the Industrial Revolution [3]

Industry 4.0 is a collective term for technologies and concepts of value chain organization. Based on the technological concepts of cyber-physical systems, the Internet of Things and the Internet of Services, it facilitates the vision of the Smart Factory. Within the modular structured Smart Factories of Industry 4.0, cyber-physical systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the Internet of Things, Cyber-physical systems communicate and cooperate with each other and humans in real time. Via the Internet of Services, both internal and cross-organizational services are offered and utilized by participants of the value chain [1].

Industry 4.0 is based on four design principles. These principles will help enterprises in identifying and implementing Industry 4.0 frameworks:

- Interoperability - It refers to the capability of machinery and related equipment to connect and communicate with people through the Internet.
- Transparency in information – It requires that information systems has to be able to create virtual copies of the physical world by butting digital data into visualised sensor data.
- Decentralization – It refers to the ability of cyber systems to independently come up with decisions and take actions on their dedicated functions. It might also mean that some tasks has to be changed from manual to fully automate and results as position loss for human.
- Technical assistance – It relates to the ability of the systems to support humans through comprehensive aggregation and visualization of information in order to have best decisions and quick solutions to problems. Technical support also focuses on the ability of cyber systems to physically support human resources by taking care of various tasks, which are time consuming or not safe for humans [3].

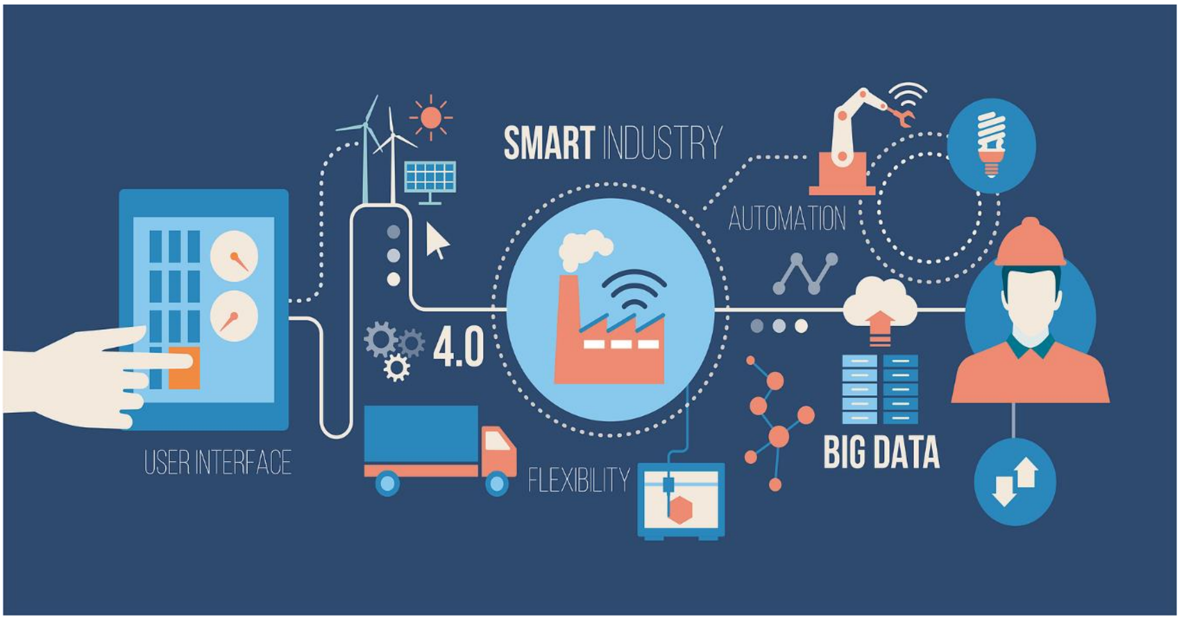

Figure 2.2 Cyber Physical System [4]

Cyber-Physical Systems (CPS) (Figure 2.2) are integrations of computation, networking, and physical processes. Connected computers and networks will observe and control the physical processes, with feedback, where physical processes affect computations and opposite. This technology can be applied the older discipline of embedded systems, whose designed purpose is not computation, such as cars, toys, medical devices, and other scientific equipment. CPS will connect the dynamics of the physical processes with software and networking to provide abstractions, design, and analysis techniques for the integrated whole [5].

Benefits from Cyber-Physical Systems:

- More efficient and safer systems.
- Reduces building cost already in design phase.
- Allows to generate complex systems that could provide new capabilities.
- Lowers the cost of computation.
- Is basis for building national or global scale CPS's [6].

Differences between a typical factory today and an Industry 4.0 factory:

In the current industry environment, providing high-end quality service or product with the least cost is the key to success and industrial factories are trying to achieve as much performance as possible to increase their profit. In this way, various data sources are available to provide worthwhile information about different aspects of the factory. In this stage, the utilization of data for understanding the current condition and detecting faults and failures is an important topic to *research. For instance, in production, there are various commercial tools available to provide OEE (Overall Equipment Effectiveness) information to factory management in order to highlight root cause of problems and possible faults in the system*.

In comparison, in an Industry 4.0 factory, in addition to condition monitoring and fault diagnosis, components and systems are able to gain self-awareness and self-prediction, which will provide management with more insight on the status of the factory. Furthermore, peer-to-peer comparison and fusion of health information from various components provides a precise health prediction in component and system levels and force factory management to trigger required maintenance at the best possible time to reach just-in time maintenance and gain near zero downtime.

Modern information and communication technologies like Cyber-Physical Systems, Big Data and Cloud Computing will help predict the possibility to increase productivity, quality and flexibility within the manufacturing industry and thus to understand advantages within the competition [1].

2.1.1 Internet of Things

The Internet of Things or IoT is an umbrella term for a broad range of underlying technologies and services, which depend on the use cases and in turn are part of a broader technology ecosystem which includes related technologies such as artificial intelligence, cloud computing, next-gen cybersecurity, advanced analytics, big data, various connectivity-communication technologies, digital twin simulation, augmented and virtual reality, block chain and more. The IoT is an additional layer of information, interaction, transaction and action which is added to the Internet thanks to devices, equipped with data sensing, analysis and communication capabilities, using Internet technologies. The Internet of Things further bridges digital and physical realities and powers information-driven automation and improvements on the level of business, society and people’s lives (Figure 2.3).

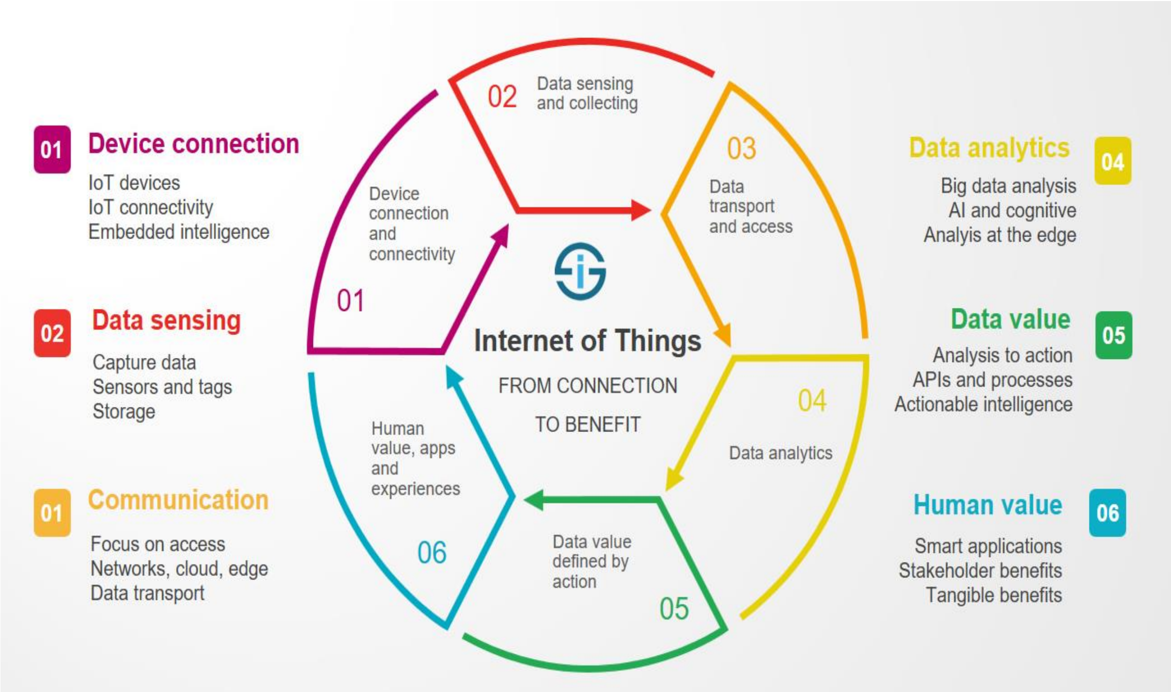

Figure 2.3 The Internet of Things from connecting devices to human value [7]

Captured, aggregated and analysed data are leveraged for several use cases, including maintenance, human, semi-autonomous and autonomous decisions (whereby data flows do not just come from IoT- enabled devices but also are exchanged between them, occur within them or are sent to them in the form of instructions), scientific research, real-time monitoring, data exchanges, new business models and far more [7].

2.2 Lean Six Sigma

Lean Six Sigma is a fact based and data driven philosophy of improvements that values most defect prevention rather than defect detection. It drives customer satisfaction and basic results by reducing variation, waste, and cycle times. Additionally, promoting the work standardization and flow optimization, what will result as competitive advantage. It is applicable anywhere when variation and waste exist, thus every employee has to be involved.

Lean Six Sigma combines the strategies of Lean and Six Sigma. Lean principle help to eliminate process wastes, when Six Sigma focuses on variation reduction in process. As a result, Lean Six Sigma helps to improve the efficiency and quality of the process [8].

Figure 2.4 Overview of Lean and Six Sigma and their link between each other [8]

2.3 Reliability Engineering Tools

2.3.1 Basics of reliability

Reliability is the likelihood that a system is operating under some certain conditions for specified period of time and during this period it is used for the manner and purpose for which it was designed [9]. Speaking about reliability in any field of engineering, there are used fundamental terms to describe reliability which are shown in Table 2.1 below.

Table 2.1 The fundamental reliability terms [10]

Reliability measure	***Description***
Failure	An event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified.
Failure Rate	The expected rate of occurrence of failure or the number of failures in a specified time period. Failure rate is typically expressed in failures per million or billion hours.
Mean Time Between Failures (MTBF)	The number of hours to pass between failures. MTBF is typically expressed in hours.
Mean Time To Failure (MTTF)	The average time to failure for a system that is not repairable. Once a failure occurs, the system cannot be used or repaired.
Mean Time To Repair (MTTR)	It is the expected span of time from a failure (or shut down) to the repair or maintenance completion. This term is typically only used with repairable systems.

A well-known way to illustrate failure rate is shown in Figure 2.5, which is named to be as “bathtub curve” and was designed to indicate the failure rates of mechanical equipment. It states that failure rate is high at the beginning of equipment lifecycle due to faulty components. The next stage is constant failure rate as components has reached their useful lifetime cycle and failures in this cycle, can be linked to random overload of the components. Finale stage in “bathtub curve” is wear-out where failures increases rapidly due to components lifecycle ends.

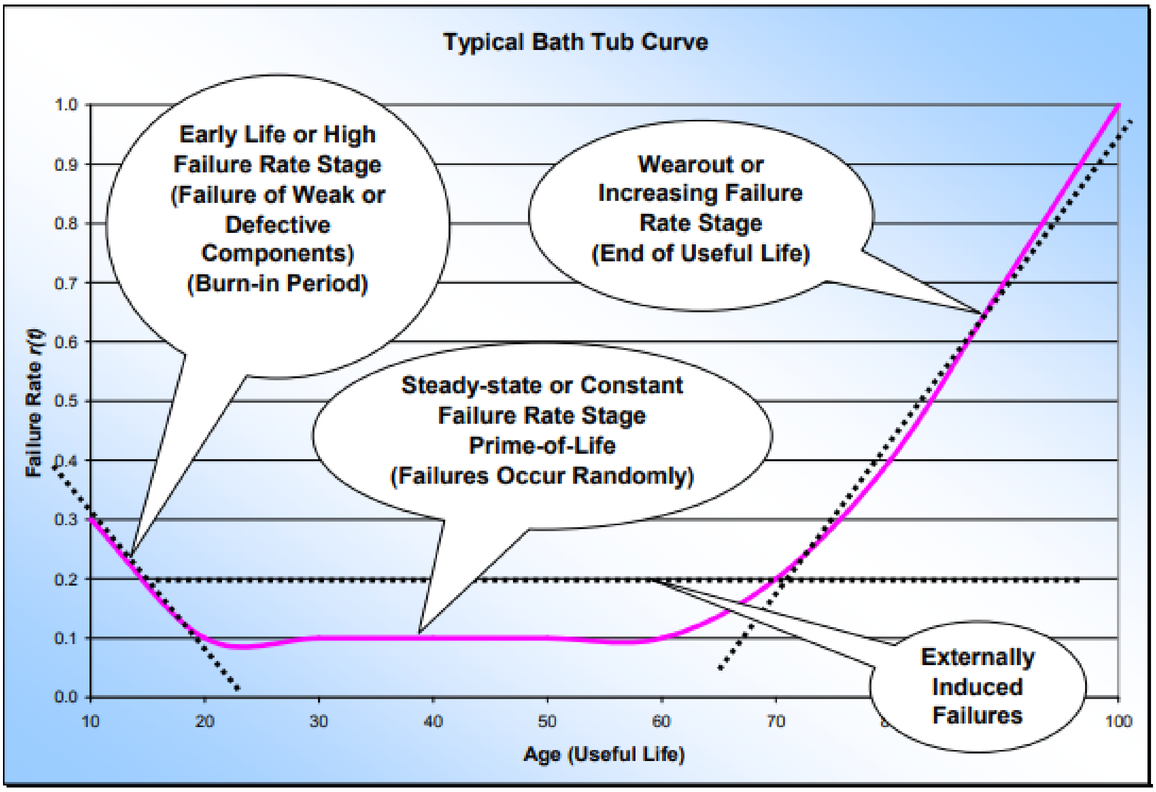

Figure 2.5 Failure rate bathtub curve [10]

Since, reliability is certainly crucial to company for achieving success and sustainability, there has been developed several tools, which help to analyse and measure reliability to improve areas of weakness. International Electrotechnic Committee (IEC 300-3-1) [11] standards state that most widely used reliability procedures are:

- Reliability Prediction
- Reliability Block Diagram
- Fault Tree Analysis
- Markov Analysis
- Fault Mode and Effect Analysis (FMEA) [12].

2.3.2 Reliability Prediction

Reliability Prediction (RB) is most widely used tool for reliability analysis. RP helps to predict the failure rate of the components and the overall system reliability. A reliability prediction can also assist in evaluating the significance of reported failures. At the end, the results obtained by performing a reliability prediction analysis can be useful when conducting further analyses such as a FMEA (Failure Mode and Effect Analyses), RBD (Reliability Block Diagram) or a Fault Tree analysis. The reliability predictions are used to evaluate the probabilities of failure events described in these alternate failure analysis models. At a certain point in time, a component or system is either functioning or failed, and that the component or system operating state changes as time evolves. Any operating component or system will eventually fail. The failed state will continue forever, if the component or system is non-repairable. A repairable component or system will remain in the failed state for a period of time while it is being repaired and then transcends back to the functioning state when the repair is completed. This transition is assumed to be instantaneous. The change from a functioning to a failed state is failure while the change from a failure to a functioning state is referred to as repair. It is also assumed that repairs bring the component or system back to an "as good as new" condition. This cycle continues with the repair-to-failure and the failure-to-repair process; and then, repeats over and over in a repairable system [10].

Previously mentioned states are shown on Table 2.1 as MTTF (Mean Time to Failure), MTTR (Mean Time to Repair) and MTBF (Mean Time between Failures). Correlation between mentioned steps are visualized on Figure 2.6 .

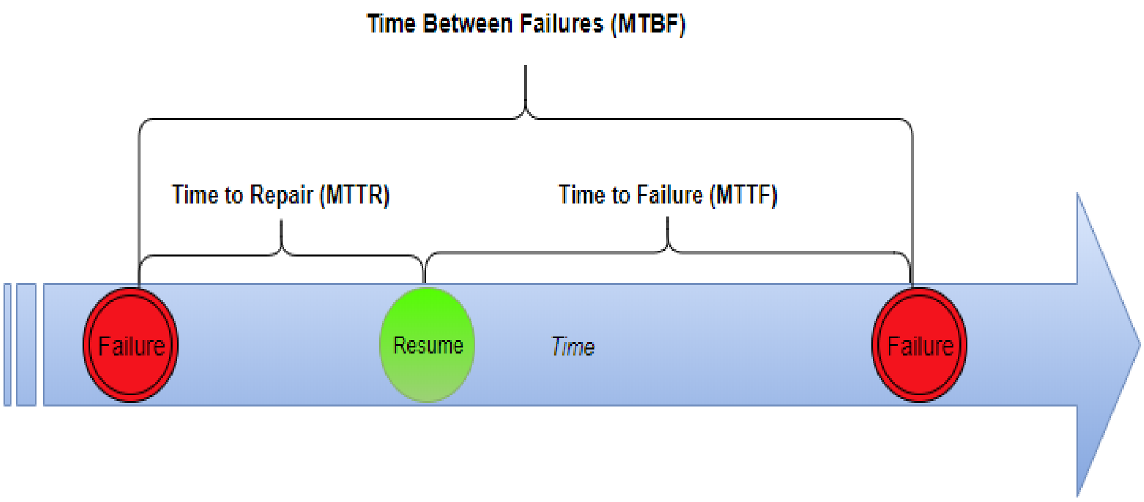

Figure 2.6 Cycle of MTTF, MTTR and MTBF

MTTF describes also the total number of working hours divided by the number of breakdowns.

$$MTTF = \frac{T_{up}}{N} \tag{2.1}$$

Where

T_{up} = total uptime

N = Number of breakdowns

MTTR defines the total time spent on performing corrective/fixing actions or preventive maintenance repairs divided by the total numbers of these actions. It typically can be used only with repairable systems.

$$MTTR = \frac{T_{down}}{N} \quad (2.2)$$

Where

T_{down} = total downtime

N = Number of breakdowns

The basic measure for repairable systems is MTBF. It concludes total time from one failure to another and often calculated as sum of MTTR and MTTF [13].

$$MTBF = MTTR + MTTF = \frac{T_{up}+T_{down}}{N} \quad (2.3)$$

2.3.3 Reliability Block Diagram

Reliability Block Diagram (RBD) is a deductive method to evaluate reliability of a system. RBD gives a visual analysis of logical structure of the system, on which individual partial systems and/or parts some reliability connections exist. This method allows representing the possible ways of successful operation of the system by those arrays (partial systems/components) the common operation of which is necessary for the operation of the system. There are several methods for evaluation of the reliability diagram. Depending on the type of the system structure, simple Boolean-like methods, analysis of the successful way of operation as well as truth tables can be used to predict the reliability and usability of the system.

The rational course of a RBD stems from an input node located at the left side of the diagram. The input node flows to arrangements of series or parallel blocks that conclude to the output node at the right side of the diagram. A diagram should only contain one input and one output node. The RBD system is connected by a parallel or series configuration. A parallel connection is used to show redundancy and is joined by multiple links or paths from the Start Node to the End Node. A series connection is joined by one continuous link from the Start Node to the End Node.

A system can contain a series, parallel, or combination of series and parallel connections to make up the network, see Figure 2.7 [10].

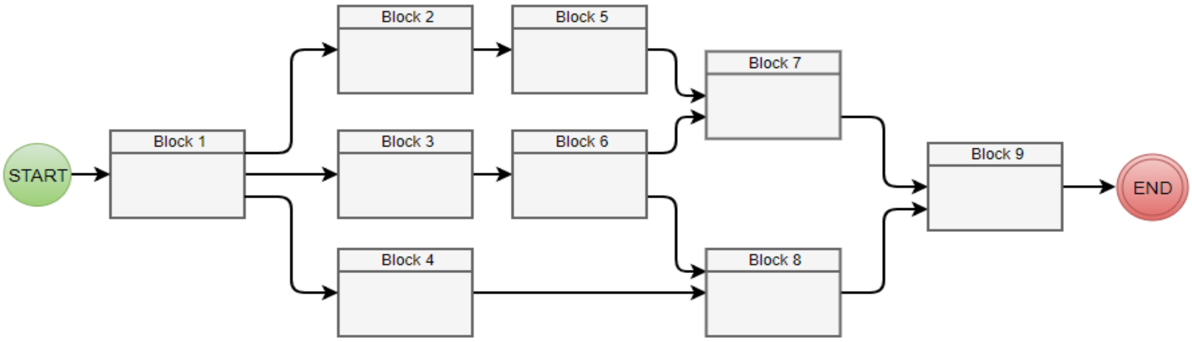

Figure 2.7 Example of Reliability Block Diagram

2.3.4 Fault Tree Analysis

Fault Tree Analysis (FTA) are logic block diagrams that display the state of a system in terms of the states of its components. Like reliability block diagrams, fault tree diagrams are a visualising design technique, and as such provide an alternative methodology to RBD.

FTA is built from top to bottom and in term of events rather than blocks. It uses a graphic "model" of the pathways within a system that can lead to a foreseeable, undesirable loss event or a failure. The pathways connect contributory events and conditions, where is used standard logic symbols as AND, OR and similar. The basic constructs in a fault tree diagram are gates and events, where the events have an identical meaning as a block in an RBD and the gates are the conditions [14].

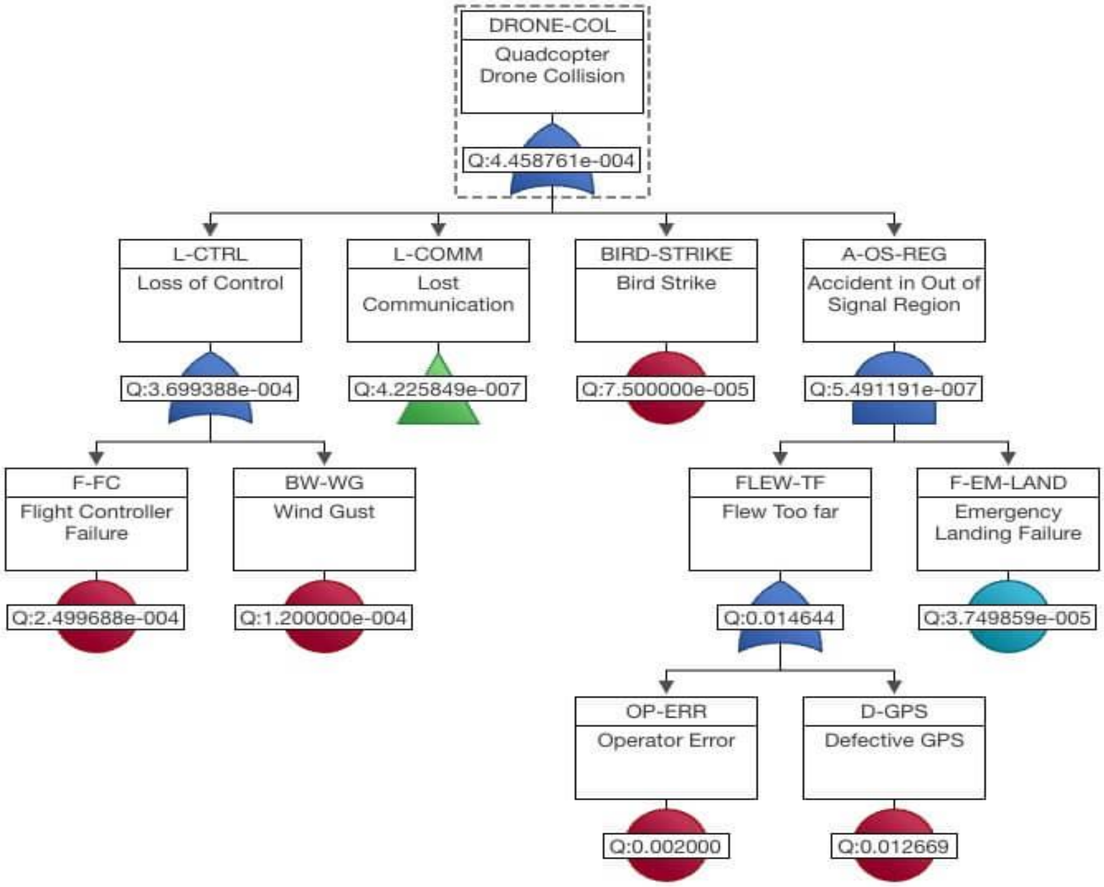

Figure 2.8 An Example of FTA [15]

FTA can be used to establish the pathway to the root cause of the failure. FTA can be used to investigate complaints or deviations in order to fully understand their root cause and to ensure that intended improvements will fully resolve the issue and not lead to other issues (i.e. solve one problem yet cause a different problem). FTA is an effective tool for evaluating how multiple factors affect a given issue. The output of an FTA includes a visual representation of failure modes. It is useful both for risk assessment and in developing monitoring programs [13].

2.3.5 Markov Analysis

Markov Analysis is a method used to forecast the value of a variable whose future value is influenced only by its current position or state, not by any prior activity that led the variable to its current position or state. In essence, it forecasts the activity of a random variable based solely upon the current circumstances surrounding the random variable [16].

Markov Analysis is mainly an inductive analysing method; it is suitable for analysing of functionally complex structures and repair/maintenance strategies. It is also widely used for competency planning in human resources development. The method uses the theory of Markov processes.

Theoretically it evaluates probability of being in a given functional status of system elements (parts, partial systems) or probability of occurrence of given events at given times or periods [12].

2013 → 2014	Plant Manager	Foreperson	Team Leader	Production Worker	Exit
Plant Manager (n = 5)	80% 4				20% 1
Foreperson (n = 35)	8% 3	82% 28			10% 4
Team Leader (n = 110)		11% 12	70% 77	7% 8	12% 13
Production Worker (n = 861)			6% 52	72% 620	22% 189
Projected Supply	7	40	129	628	

Figure 2.9 An example of Marko Analysis in manufacturing operations [17]

2.3.6 Failure Mode and Effects Analysis

Failure Mode and Effects Analysis as FMEA, is a reliability procedure which gives an estimation of potential failure modes for processes and also how they might affect its outcome on products. With failure mode analysis, this tool defines the effect of each failure and identifies single failure points that are crucial to achieve targeted goals and staff safety. FMEA is most suitable when it is examined what effects have faults of basic materials, parts and equipment on the next functional level of higher, and also what fault mechanism can be found at this level. Most commonly FMEA is applied to equipment, facilities or processes, it means it can be used to analyse a manufacturing operation and its effect on product or process. The outcome of FMEA can be used as a basis for design or further analysis or for guidance of resource deployment [18].

IN FMEA analysis, each failure what is studied, is considered to be the only failure in the system, what mean that it is single failure analysis. FMEA utilizes inductive logic in a "bottoms up" approach. Beginning at the lowest level of the system hierarchy and from a knowledge of the failure modes of each part, the analyst traces up through the system hierarchy to determine the effect that each failure mode will have on system performance [9].

FMEA analysis has to be team based to conduct knowledge and experiences from variety of specialist, for example engineers from area of design, manufacturing, quality and repairs. Never the less, FMEA is team based to gather data from different areas, there has to be one person who is responsible of collection of the data.

	Failure Mode and Effect Analysis																
													Action Results				
Rev no.	Process Step, Operation, Function or Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Class	Potential Cause(s) of Failure	Occurrence	Current Controls/ Evaluation Method	Detection	S x O	RPN	Recommended Action(s)	O	D	Diff	PCT%	RPN

Figure 2.10 FMEA form

FMEA is conducted in a form of a table (see Figure 2.10) where every row indicates single failure mode which is described by several parameters in columns. When failure modes are established, risk reduction can be used to eliminate, control or reduce the potential failures.

There is three aspects what are used to evaluate failure modes: Severity (S), Occurrence (O) and Detection (D). Severity stands for criticality of a failure, occurrence is how frequently failure may occur and detection means what kind of controls we have to detect the failure. Severity, Occurrence and Detection parameters are evaluated on a scale of 1 to 10. Characteristic of ranks from 1 to 10 are explained in Table 2.2, Table 2.3 and

Table 2.4.

Table 2.2 Ranks for severity estimation [19]

Severity of Effect on Product	Rank	Severity of Effect on Process
Potential failure mode affects safe item operation without warning	10	May endanger operator/machine without warning
Potential failure mode affects safe item operation with some warning	9	May endanger operator/machine with warning
Loss of primary function (item inoperable, but does not affect safe item operations)	8	100% of production may be scrap. Stop production or stop shipment
Degradation of primary function (item still operates, but at a reduced level of performance)	7	Portion of production run may be scrapped. Decreased line speed or additional manpower required

Severity of Effect on Product	Rank	Severity of Effect on Process
Loss of secondary function (item still operable, but comfort functions do not work)	6	100% of production run may require off-line rework
Degradation of secondary function (item still operates, but comfort functions perform at reduced level)	5	Portion of production run may require off-line rework
Appearance item or audible noise (annoys more than 75% customers)	4	100% of production run may require rework in-station before it can be processed
Appearance item or audible noise (annoys 50% customers)	3	Portion of production run may require rework in-station before it can be processed
Appearance item or audible noise (annoys less than 25% customers)	2	Slight inconvenience to process, operation or operator
No discernible effect	1	No discernible effect

Table 2.3 Ranks for occurrence estimation [19]

Likelihood of Failure	Occurrence of Causes	Occurrence Rank
Very High	>1 per 10	10
High	1 in 20	9
	1 in 50	8
	1 in 100	7
Moderate	1 in 500	6
	1 in 2000	5
	1 in 10000	4
Low	1 in 100000	3
	1 in 1000000	2
Very Low	Failure eliminated by preventive control	1

Table 2.4 Ranks for detection estimation [19]

Detection by Process Control	Detection Rank
No current process control; cannot detect; is not analysed	10
Failure and errors are not easily detected (e.g. random process audits)	9
Post-processing failure mode detection by operator using visual, tactile, or audible means	8
In-station failure mode detection by operator using visual, tactile, or audible means, or by attribute gages	7
Post-processing failure mode detection by operator via variable gages or in-station by operator using attribute gages	6
In-station failure mode or cause detection by operator via variable gages. Also gauging on set up; first piece inspection	5
Post-processing failure mode detection by automated controls that detect nonconforming parts and prevent further processing	4
In-station failure mode detection by automated controls that detect nonconforming parts and prevent further processing	3
In-station cause detection by automated controls that detect an error and prevent bad parts from being made	2
Error prevention via fixture design, machine or part design. Bad parts cannot be made.	1

Result of and FMEA analysis is a calculated number RPN, what is a multiplication of S, O and D.

$$RPN = S \times O \times D \quad (2.4)$$

Where

RPN – Risk Priority Number

S – Severity

O – Occurrence

D – Detection

Further work with the most critical failure modes is realized according to RPN. Several strategies exist for the mitigation of risk, for example:

- High Risk Priority Numbers
- High Severity Risks (regardless of RPN)

- High Design Risk (Severity x Occurrence)
- Other Alternatives (S, O, D) and (S, D) [13].

As mentioned the outcome of FMEA is RPN number, what is product of three parameters what measure the risk of a failure or fault. Since, RPN is result of multiplication of three parameters it has no meaning as a number, it is useful only for comparison of two solutions. Although, FMEA is widely used and successful tool, but the most value will bring in as management tool, not as technical prediction tool. It is ideal tool to evaluate systems for implementing continuous improvement and lean strategies for reliability engineering.

2.3.7 Selection of suitable Reliability Engineering tool

As the task of this thesis is to develop IoT based system for monitoring and management of compressed air system. First of all, it is needed to establish starting points for IoT system designing in the spirit of reliability. In order to achieve it, the author of the thesis has brought out five most commonly used reliability engineering tools what might be suitable for this kind of design application. The author has built the Table 2.5, to have better overview of advantages and disadvantages for decision making.

Table 2.5 Pros and Cons table for RBE tools [13]

RE Tool	Advantages	Disadvantages
Reliability Prediction	• Time and cost are low • Good for preparing maintenance strategy's	• No fault cause or effect analyse • No detection analyses
Reliability Block Diagram	• Able to analyse combine events • Variety of system configurations are demonstrated • Boole-algebra allows to value simply functional and non-functional units	• No cause or effect analyse • Need to know reliability functions for every event • Do not examine complicated repair and maintenance strategies • No detection analyses
Fault Tree Analysis	• Identifies failures in logical way to find root causes • Demonstrates redundancy systems • Can calculate system Risk Number • Needs accurate data	• Big trees cause very detailed analysis • Do not present state transitions • Do not examine complicated repair and maintenance strategies • No detection analyses

RE Tool	Advantages	Disadvantages
Markov Analysis	• Demonstrates multi stage events • Values complicated repair events	• Can be complicated due to big number of system states • No logical solution to problems
Fault Mode and Effects Analysis	• Identifies connections between reasons and effects • Demonstrates previous unknown event outcome • Is a systematized analysis • Allows singe mode analyses • Good for design processes	• Data can be too much • Analyses may be too complicated

As the aim of the IoT system would be to gather necessary data for preventive and improvement actions. The selected tool has to be suitable for system/process designing and foremost, should provide comparison between current and new solutions or compare different risk levels with connecting failure and cause. Also, should not need vast amount of data for using as it should be simple to use. Improvement actions has to be integrated into the tool. However, this tool should be re-usable several times if needed.

Table 2.6 Reliability engineering tool evaluation for selection

RE Tool	Can be used for design	Cause and effect analyse	Logical/easy to use	Integration of improvements
Reliability Prediction	No	No	Yes	Yes
Reliability Block Diagram	No	Yes	No	No
Fault Tree Analysis	Yes	Yes	No	No
Markov Analysis	No	Yes	No	No
Fault Mode and Effects Analysis	Yes	Yes	Yes	Yes

For choosing the most suitable engineering tool for the IoT system development, author gathered together all required parameters for the tool and put them together to
Table 2.6 for evaluation. From the evaluation came out that, for us would be the best tool FMEA, as it complies with all the parameters. Further on will be FMEA tool used as basis for the framework development.

Addition to design tool selection, during the marking advantages and disadvantages, the author of the thesis discovered that FTA tool could be useful for risk and improvement management after the desired IoT system deployment for data recording. As FTA needs accurate data for conducting analyses, what we do not have at the moment. It will be considered to add FTA for future framework as second reliability engineering tool and can be used when accurate data is gathered.

3 IOT BASED FRAMEWORK DEVELOPMENT

As the glass manufacturing plant processes are continuously constant, its success and efficiency depend on its supportive system reliability to function. With reliable system can be achieved sustainable and stable system operation, which will result in quality raise and also reduction of production losses. Current thesis is working on to raise the reliability of compressed air systems to reduce production losses related to it. In order to improve the system by preventive actions or with redesigning, it needs data what can be used for this purpose for further analyses. Since, at the moment the data for improvements is missing and all the actions are done in order to "*extinguish the fire"*. To start fixing problems in preventive way, this thesis has focused to develop a framework for designing an IoT structure for compressed air, what will provide required data for previously mentioned problem to solve. For framework generation is used knowledge from Industry 4.0, IoT and Lean Six Sigma principles in order to have desired outcome.

The main idea behind developed framework is represented in Figure 3.1 and as it can be seen the first cornerstone for further framework is on reliability analyses with FMEA tool. For better understanding the scope of work to be covered in framework, will be explained step-by-step in following part:

1. In order to perform FMEA analyses an expert team has to be gathered to define input failure modes for the analyses. To focus on right input data are given three directions as Preventive maintenance, Optimization and Investments.
2. FMEA analyses are conducted by evaluating failure mode three parameters as Severity, Occasion and Detection in scale of 1 to 10. Respectively of RPN result, will be provided improvement actions in order to reduce the RPN.
3. According to improvement actions from FMEA and status of current equipment, it will be used to design adequate and desired IoT system. For system monitoring to take preventive actions and for data collection in order to improve.
4. Next step would be the deployment of designed IoT system to gather crucial data for the further analyses to take preventive actions or for improvements.
5. Data analyses on certain purpose can be performed or what may be new input data for new FMEA (1.) analyses with related topic.
    - 5.1 Preventive maintenance actions from data.
    - 5.2 Equipment/System optimization can performed with data.
    - 5.3 Investment for further improvements can planned with data.

6. Data from IoT system can be used for FTA and risk calculations in purpose of continuous improvements.

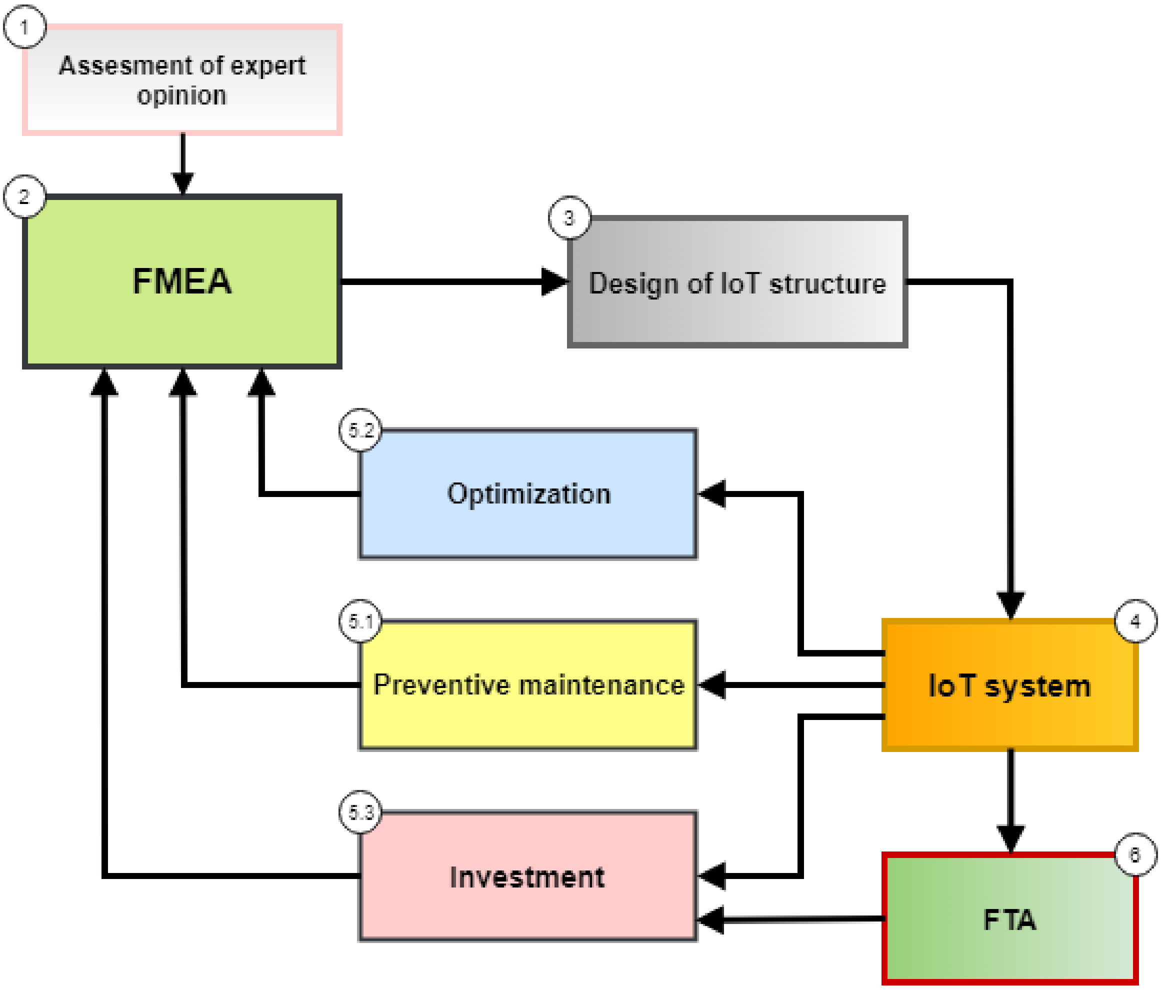

Figure 3.1 IoT based framework for compressed air system

In this thesis, this framework will be used for developing an IoT solution to compressed air systems monitoring and management. Never the less, this framework can be implemented on any kind of system where an IoT integration or reliability improvements are desired. Provided framework goes hand-in-hand with Continuous Improvement and Lean Six Sigma methodologies for reducing waste, variability and uncertainties. As it is meant to repeat the cycle when initial solution is finished, in order to improve again.

4 FRAMEWORK DEPLOYMENT ON COMPRESSED AIR SYSTEM

Next step will be deploying developed framework on compressed air system in Järvakandi O-I plant for IoT integration. Before that, will be given an overview of company itself together with describing main production processes to understand their connections to described compressed air system. Further on will be covered framework steps as conducting FMEA and IoT design with payback calculations.

4.1 Overview of O-I Production Estonia AS

Järvakandi glass plant history goes back 1879 when it started its first glass furnace for production of fisherman glass buoy’s. Later on, in 1900’s plant switched its production to sheet glass, what was used for windows. In 1991 Järvakandi Klaas founded joint venture with Ahlström Riihimäen Lasi OY and invested into it to start producing glass containers for the region. Since the joint venture between Järvakandi Klaas and Ahlström was successful they managed to build growth. This lead to Owens-Illinois to acquire the plant with great potential to its own corporation family in 1995. As the world leading glass manufacturer owning 80 plants in 23 countries, had a business case to spread its market and raise the quality level here in northern region of Europe. 2015 they totally rebuilt the most of the plant, where they installed state of art gas-oxygen fuelled furnace, with total investment of 25 million euros. Today the plant is capable of producing up 270 tons of glass, which is around 700k containers, in one day. For smooth operation of the plant it has 160 employees, additionally the support from plants all over the Europe.

Figure 4.1 O-I Production Estonia AS Järvakandi plant entrance

4.2 Main production processes description

In this part, the main production processes are described as they follow on Figure 4.2. To understand better how main production processes are linked to usage of compressed air, it will be explained together with processes of which type of compressed air is used and why. Terms LPS (Low Pressure system) and HPS (High Pressure system) will be used for explanations.

Flow begins with production order which states what kind of glass is produced, flint or extra-flint. Following step is raw materials weighting and mixing, where HPS air is essential to operate valves and vibrators for dosing and mixing. Correctly mixed and dosed materials move to furnace where it is melted in 1500 degrees. Furnace needs number of sensors to operate precisely and accurately to maintain glass level and temperature, but due to high temperatures, these sensors need cooling and for this application HPS air is used. From furnace, molten glass flows to forming machines, which are the main and biggest compressed air consumers in the plant. Forming machines are operating with two different pressure ranges, such as LPS for forming operations and HPS for piloting and rejection operations. Next process is called Hot End coating, which means that hot containers are covered with thin layer of tin based mix, to perform better with dynamic loads. All containers travel next to annealing lehr to release stresses caused by glass properties and its distributional aspects. Straight from annealing, containers are covered with so called Cold End coating mix, what gives to them non-sticking surface, what allows fast and trouble-free handling in filling lines. This coating system uses HPS air for spraying and mechanical movements. There on, containers go thru quality inspection machines what are using HPS air for its main and supportive functions to inspect and reject containers. All containers that are passing quality requirements will be packed by layers on pallet. Gathering containers to layer format and lifting them to pallet, this machine need great amount of HPS air to perform correctly and safely. All pallets are packed with thermo shrinking foil in dedicated machine which uses also HPS air for moving and lifting operations. Last step in main production process is moving pallets to warehouse with forklifts.

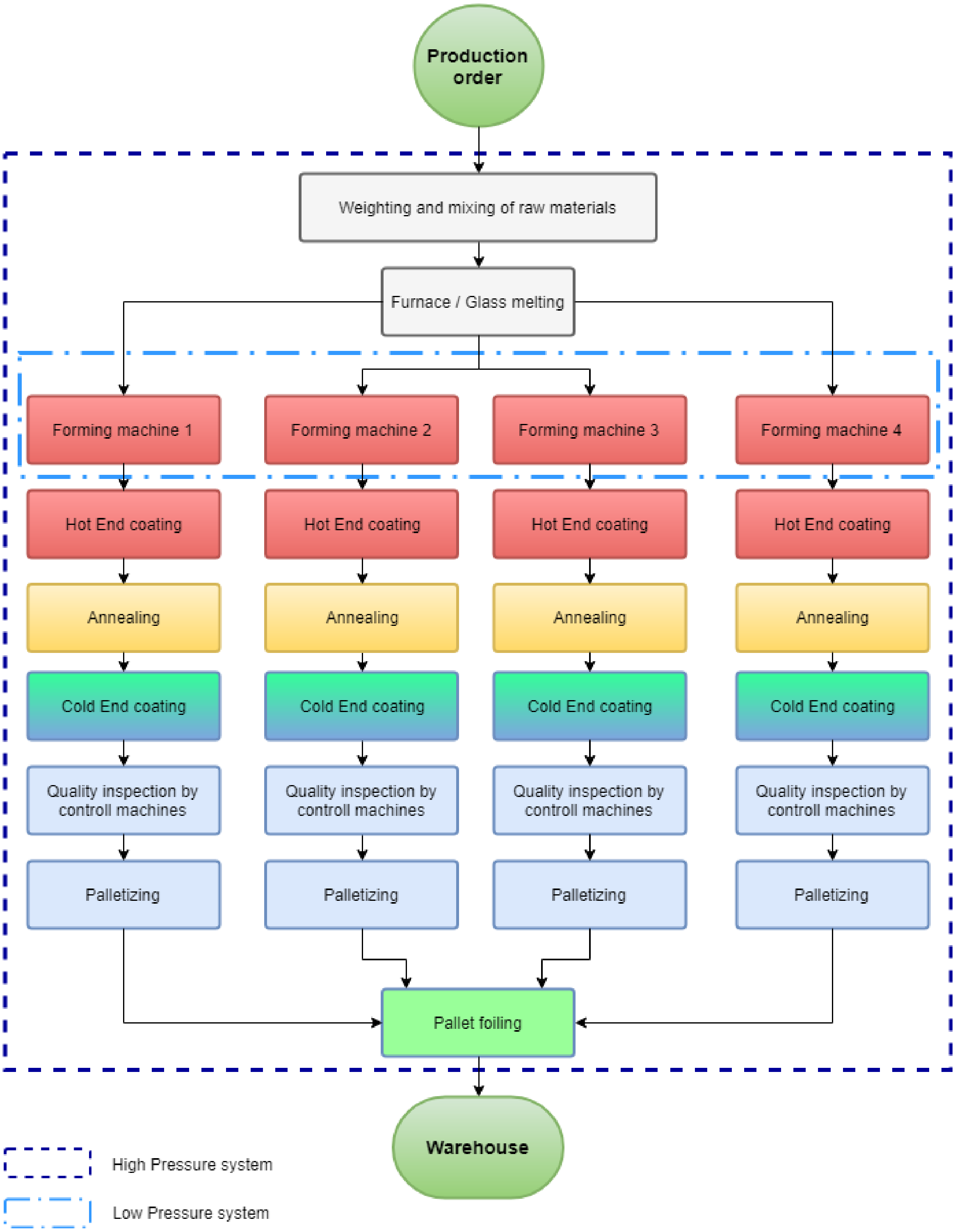

Figure 4.2 Main production process with compressed air usage areas

It can be clearly seen that seven main production processes out of eleven, are using compressed air to operate. This process chart is not covering several supportive structures such as mould shop, where forming moulds are repaired and prepared for production. This department uses grinding tools what are compressed air driven, which means they cannot operate without it.

Generally, 64% of the plant is dependent on compressed air and to keep efficient, sustainable and stable production, it is crucial to have constant and continuous compressed air supply at all times.

4.3 Detailed description of compressed air systems

As it was described in pervious section, the plant has two independent compressed air systems (see Figure 4.3), what are called LPS what is operating in rage of 4.3 to 4.7 bars and HPS what is operating in range of 6 to 7 bars. Justification for having two separate systems is linked with main process in production, what are forming machines. Since in forming operation is not needed greater pressure than 3.5 bars, it clearly makes no sense in energy wise to produce for this operation air with greater pressure. Another aspect is also that LPS air consumption in forming process is around 2.5 times greater than HPS air consumption.

Both systems all together has total 9 oil lubricated screw compressors with shaft power of 1,42 MW. Four of them is connected to LPS and other five to HPS, see Table 4.1.

Table 4.1 Compressor park in 2017 April

	#	Brand	Model/Year	Max Pressure [bar]	Motor Power [kW]	Capacity [m^3/min]
Low Pressure System	1	Tamrotor	L 200 / 1994	4	200	36,3
	2	Tamrotor	L 200 / 1992	4	200	35,5
	3	Tamrotor	LG 200 / 1992	4	200	43,3
	4	Atlas-Copco	GA 250 / 1996	7,5	250	45,1
				LPS Total	**850**	**160,2**
High Pressure system	5	Tamrotor	FL 75 / 1996	7,5	75	12,2
	6	Tamrotor	FL 75 / 1996	7,5	75	12,2
	7	Atlas-Copco	GA 75 / 1999	7,5	75	14,1
	8	Garden Denver	ESD 90 / 2005	7,5	90	16,7
	9	Garden Denver	ESN 250 / 2008	7,5	250	43,4
				HPS Total	**565**	**98,6**
				Total	**1,42**	**MW**

Both systems are controlled with Multi Pilot systems, which allows to prioritize compressors to starting sequence. These Multi Pilot systems starts and stops compressors according to the pressure of the system, it also gives visual overview of which machine is operating under load and which is not, also displays current pressure in the system. All compressors are equipped with SOCOMEC energy reading devices, what allows to monitor this parameter. Energy consumption data is at the moment only parameter from the compressed air systems, what is collected for the analyses and daily overview.

The whole infrastructure and compressor park is rather old and its design is outdated for most optimal operation for this purpose. It can be seen from the problems, what has been occurring after plant rebuild in 2014, when rated production capacity raised. Production capacity raise is linked to bigger forming machines what now need more compressed air than before and are quite more sensitive to any errors caused by pressure variations in air systems. Secondly, as it was mentioned previously, the compressor park is old and need constant supervision to prevent major failures. Due to lack of qualified operators in the plant, this part may suffer and the result would be failures, what can affect production. Third aspect is lack of information to perform preventive actions, as warnings or any kind of parameters what are showing signs of failure.

As we cannot rely on human memory and senses all the time, we need to start gathering this crucial data in digital form for preventive actions and further analyses for investments to raise the reliability of the system. Main topic of this thesis is to develop an IoT system what could provide data for preventive actions, optimization and further investments.

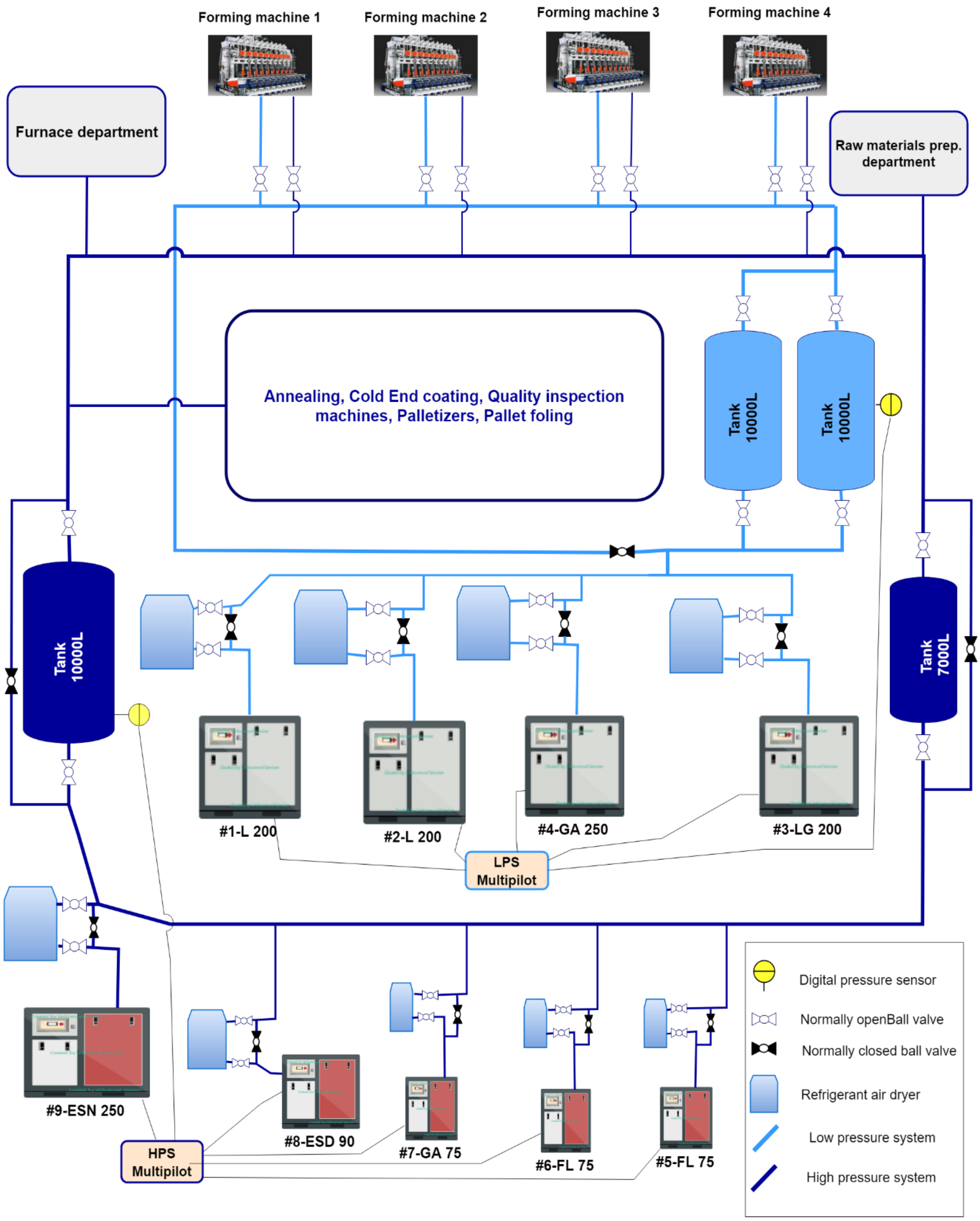

Figure 4.3 Compressed air systems currently.

4.4 FMEA analyses

As FMEA has to be team based to have knowledge from different areas related to problem, the author of thesis gathered together team from production, automation, energy and maintenance departments. Additionally, were included two sub-contractors, who are experts on screw compressors and are doing maintenance to our machines.

Three main aspects - optimization, preventive maintenance and investments, what IoT based system should fulfil, were introduced to all FMEA team members to define inputs for the analyses. Physical data about previous failures from the past and personal experience was used for defining modes also.

Failure modes defined by the team members are following:

- Compressor failure / Not performing properly
  - Overheating
  - Motor overload
  - Motor bearings worn-out
  - Screw inefficient work/ worn-out
  - Screw bearings worn-out
- System
  - Pressure in LPS drops below minimum
  - Inefficient pipe system to deliver large amounts of air in short periods

Next it was performed FMEA analysis to defined failure modes to get RPN number about current situation on, see Table 4.2. Then were developed possible solutions/recommendations to reduce RPN on each specific failure mode, see Table 4.3.

Table 4.2 Failure modes with calculated RPN

#	Process Step, Operation, Function or Requirements	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) of Failure	O	Current Controls/ Evaluation Method	D	RPN
1	Compressor operation	Overheating	Stopping compressor operation	8	Not enough cooling air/Cooling system stuck/Low oil/Worn out screw	5	Measuring by thermo gauge, but no recording or warning delectation	6	**240**
2	Compressor operation	Motor overload	Stopping compressor operation	8	Screw worn-out / overpressure/ bearings failure	3	Measuring compressor current for energy readings but no evaluation related to problem	6	**144**
3	Compressor operation	Motor bearings worn-out	Can cause motor failure and cause other failures in machine	7	Overload/overheating motor or no lubrication to bearings	3	Twice a year vibration is measured	4	**84**
4	Compressor operation	Screw un-sufficient work/ worn-out	Excessive energy consumption compared to output capacity/ Lack of air in system	6	Screw mechanically worn out/Load-unload valve malfunctioning	4	No current control	8	**192**
5	Compressor operation	Screw bearings worn-out	Can cause screw failure and cause other failures in machine	8	Lack of lubrication or normal wear due time	2	Twice a year vibration is measured	4	**64**
6	LPS pressure	Pressure in system drops below minimum	Some production lines can be stopped interrupted	10	Compressor failure/ not enough capacity due to compressor failure	5	Multipilot system should start additional compressor if available	4	**200**
7	Pressure drops in LPS	Inefficient pipe system to deliver large amounts of air in short periods	Some production lines can be interrupted	6	Not adequately designed delivery system	2	Pressure is measured right before consumer and gives visual alarm	4	**48**

Table 4.3 Improvement actions and new RPN's

#	Recommended Action(s)	Action Results			
		S	O	D	RPN
1	Install digital reader with integration with direct feedback system	8	3	2	48
2	Install digital temperature sensor with direct feedback and data logging. Data has to be analysed with upper and lower parameters to evaluate situation +data logging	8	3	1	24
3	To install vibration sensors on motor with real time monitoring and data logging	7	1	2	14
4	To install output capacity flow meters and digital pressure sensor on machine with constant reading, integrate reading with compressor work status and current readings.	6	3	1	18
5	To install vibration sensors on motor with real time monitoring and data logging	8	2	1	16
6	There is second HPS system where air can be taken to substitute compressor loss/pressure loss in the system in short period. Automated discharging system should be developed.	10	1	1	10
7	Install digital pressure sensors and flow meters. Integration to logging system for data analysis.	6	2	3	36

4.4.1 FMEA results

Totally were defined seven failure modes what are directly linked to compressed air systems reliability. To these failure modes were offered improvement actions as a team effort and new RPN’s were calculated accordingly to recommended actions, see

Table 4.3. The results of new RPN’s were compared with old RPN number on Figure 4.4 to find out, what are the most critical parameters to observe and integrate into IoT system.

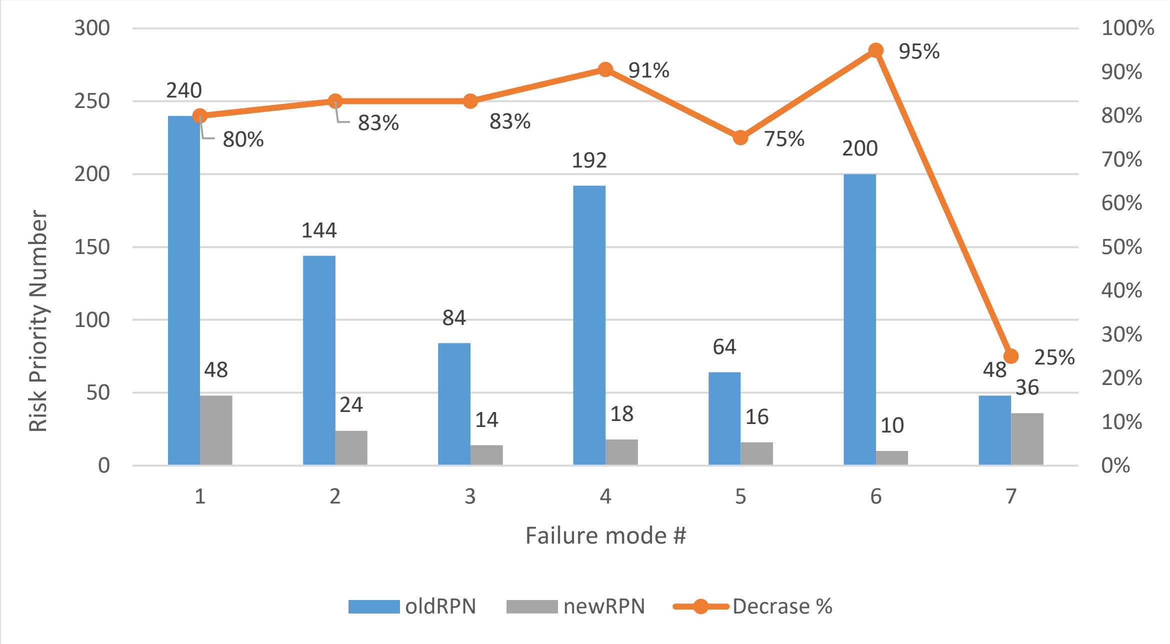

Figure 4.4 RPN difference.

It can be clearly seen that offered improvement actions on failure modes would reduce the risk levels on different modes from 25 to 95 percent.

During the analyses the team realized that failure mode 6 will go out of this thesis scope, since this is more related to re-designing compressed air infrastructure. Failure mode 6 needs also additional information what can be gathered from planed IoT system to conduct FTA and FMEA analyses for the improvements. Failure mode 6 topic can be source for further investigation in order to reduce risks related to compressed air systems. According to team decisions, the author of this thesis will continue to develop IoT system with failure modes 1 to 5 and 7.

Conclusion taken from FMEA analysis to develop IoT system prior to fulfil stated framework are following:

- If digital temperature sensors are not present in compressor, then install to avoid machine overheating or other related failures to that aspect. Start logging this data into continuous observation system for preventive actions. Immediate warning delegation to operator/manager about out of limit readings.
- Integrate energy readings from all compressors into continuous observation system for data analysis. Data will help to optimize compressors work and detect failures related to mechanical wear. Data is initial for preventive action planning. Immediate warning delegation to operator/manager about out of limit readings.

- Install vibration sensors to motor and screw element to detect components wear. Crucial for preventive actions. Immediate warning delegation to operator/manager about out of limit readings.
- Install digital flow meters and pressure sensors on each machine with data logging to detect screw element wear or failures. Data will give an overview of compressors capacity currently in system, will help to optimize system parameters. Immediate warning delegation to operator/manager about out of limit readings.
- Install digital pressure sensors and flow meters before forming machines in LPS for data logging. With data can future investments planned and designed. Immediate warning delegation to operator/manager about out of limit readings.

4.5 IoT system development

Next step is to find out what kind of equipment plant already have in place and what is need additionally to build desired IoT system for compressed air management. Further on, this data will be one of the base information for investment calculations to external companies.

A survey was conducted to indicate what parameters are measurable from compressors already and what needs to be done. Survey results can be seen on Table 4.4.

Table 4.4 Survey about sensors in compressors.

#	*Brand*	*Temperature sensor*	*Energy reading*	*Vibration sensor on motor*	*Vibration sensor on motor*	*Flow meter*	*Pressure sensor*
1	Tamrotor	Yes	Yes	No	No	No	No
2	Tamrotor	Yes	Yes	No	No	No	No
3	Tamrotor	Yes	Yes	No	No	No	No
4	Atlas Copco	Yes	Yes	No	No	No	Yes
5	Tamrotor	Yes	Yes	No	No	No	Yes
6	Tamrotor	Yes	Yes	No	No	No	Yes
7	Atlas Copco	Yes	Yes	No	No	No	Yes
8	Garden Denver	Yes	Yes	No	No	No	Yes
9	Garden Denver	Yes	Yes	No	No	No	Yes

From the survey we can see that totally are 54 inputs from compressors and 24 of them are already reachable digitally. It means 30 sensors are needed to install additionally to have all parameters measured in compressors.

In FMEA analysis came out also problems with LPS and there we need to install additional 4 flowmeters and 4 pressure sensors to forming machines to gather required data. It means that **38** sensors are required to install out of **62**, prior to full fill desired goal.

All together this IoT system has to gather data from 62 inputs and turn it to visualized interface where each input is linked to its source. It has to have option to define upper-lower parameters with warning delegation to mobile phone via SMS and e-mail for preventive actions. Most definitely this system has to save all logging data to secure storage for further analyses. By the rules what are dictated in corporation, it can be access only in internal network with computers, tablets or smartphones or via VPN from external connections. Components for the system has to be selected in keeping mind further structure development to integrate more equipment with it. System has to comply with Internet of Things general rules and for that sample structure is shown in Figure 4.5.

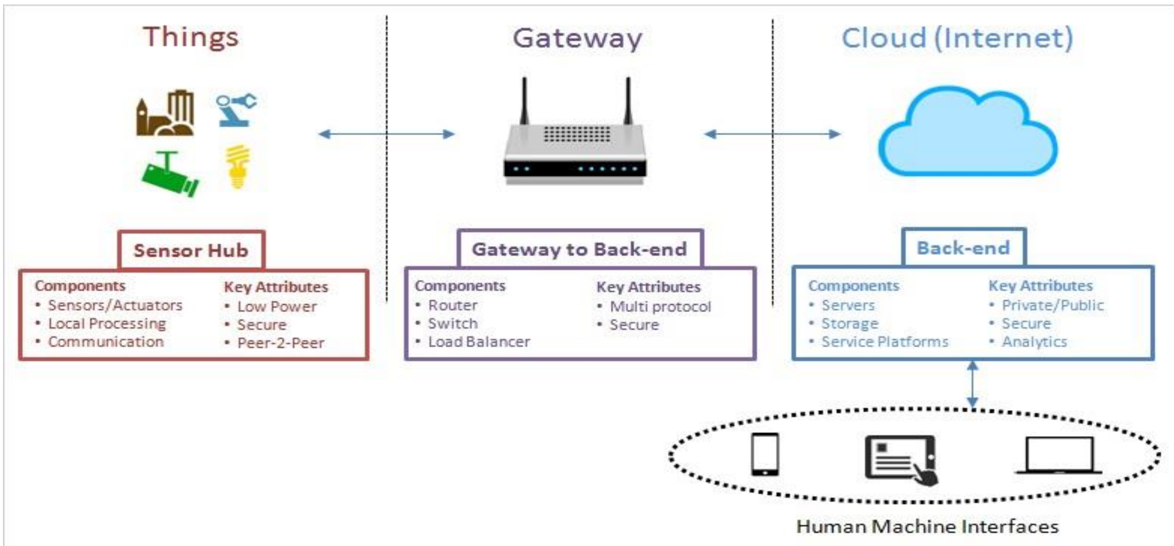

Figure 4.5 Internet of Things general schema [20]

As a next step, was gathered quotations from external companies to develop and build this kind of system, since locally in plant we do not have such know-how and experience. Quotations were asked from three enterprises with the aim of selecting the lowest one for further corporation. Offered solution from contractor is drawn out on Figure 4.6, where is shown sensors locations, gateways and general cloud architecture.
Lowest offer is shown in simplified form at Table 4.5 to understand the scales of investments needed.

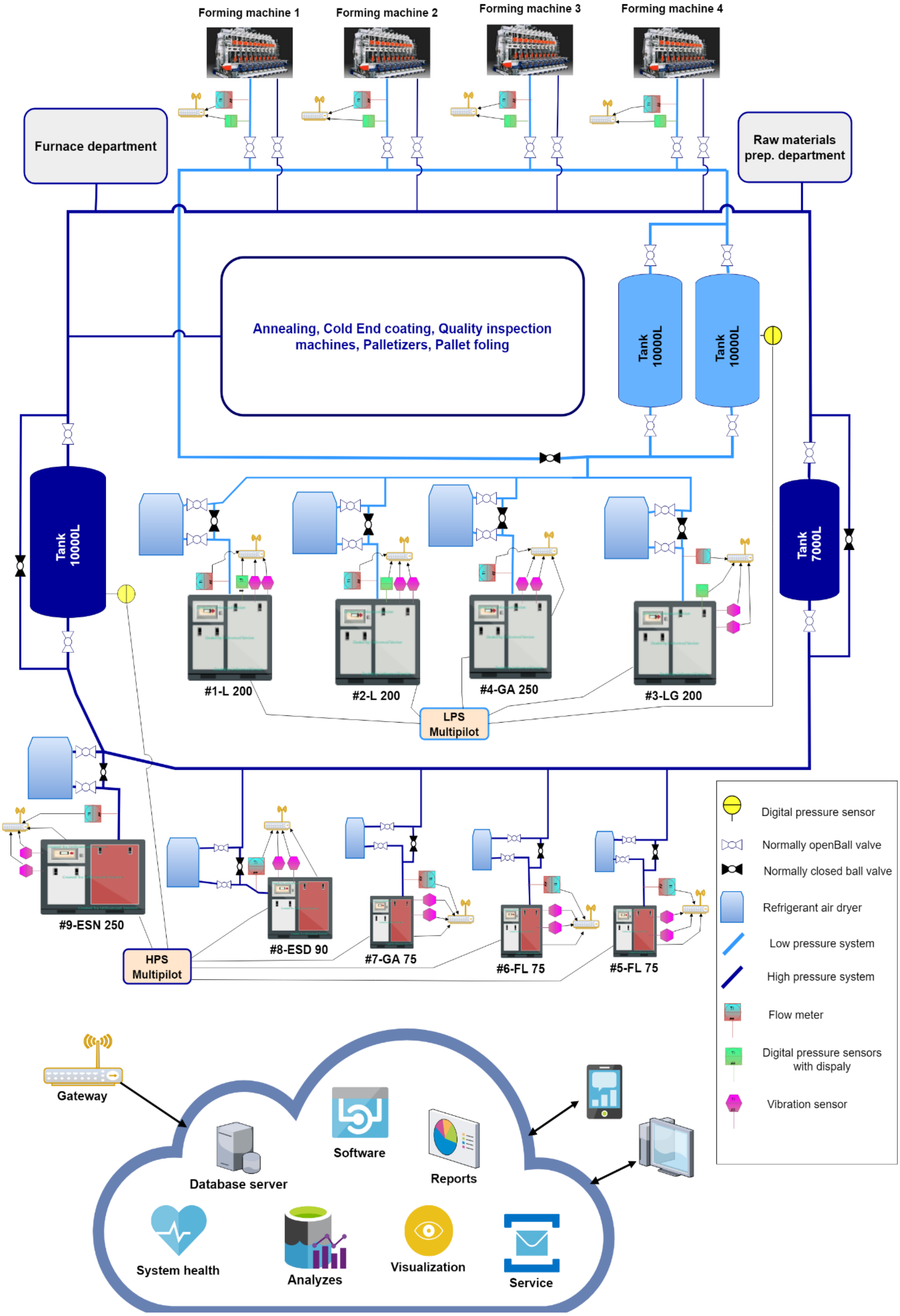

Figure 4.6 Designed IoT system for compressed air

Table 4.5 The cost of IoT system

Component	***Price***
Sensors, connectors, wiring	9 270 €
Data Acquisition systems	4 100 €
Data processing equipment	1 800 €
Software solution	7 130 €
Installation	5 000 €
Total	***27 300 €***

In order to find the payback period, the estimated savings should be calculated. For that we have to find out what is the estimated time saved from production interruptions related to compressed air systems with new monitoring system.

We know that in 2017 was production stopped in 0.2% from total production time, because of failures in compressed air systems. From FMEA analyses we can also see that we could reduce the risks averagely 73% in the system to failure and if we take that this will reduce the stopped time by half of the average percent of the improvements. We take it as half because we cannot remove human mistake factor with provided solution. It means payback period can be calculated with 36.5% reduced stopped time in production by compressed air systems.

In O-I cost is calculated per ton, it means we need to find stopped hours, yearly average tons per hour and price per ton.

In 2017 plant was working 8760 hours, which is 24h 365 days in a row, 0.2% from this time will make 17.52 hours. Average tons per hour was 9.21 and average cost per ton is 263€.

$$Total\ cost\ of\ stops = Stopped\ time\ hour \cdot Avg\,\frac{tons}{h} \cdot Avg\ cost\,\frac{€}{ton} \qquad (4.1)$$

$$Total\ cost\ of\ stops = 17{,}52 \cdot 9{,}21 \cdot 263 = 42449\ € \qquad (4.2)$$

With proposed system we could reduce stopped time by 36.5%, according to that we can calculate out savings and payback period. As cost of system is 27.3k€.

$$Total\ yearly\ savings = Total\ cost\ of\ stops - 36.5\% \quad (4.3)$$

$$Total\ yearly\ savings = 42449€ - (42449€ \cdot 0{,}365) = 15494€ \quad (4.4)$$

$$Payback\ period = \frac{Cost\ of\ system \cdot year}{Total\ yearly\ savings} = \frac{27300€ \cdot year}{15494€} = 1{,}8\ years \quad (4.5)$$

It is clear to see, that the investment payback time is under two year, which would make it very reasonable investment to make, when general plant stability will raise and production losses can be reduced. As one of the part in payback calculations is ROI (Return on Investment), it will be calculate out in this thesis as well. Due to payback time is over one year, ROI is calculated for two year period.

$$ROI = \frac{(Gain\ from\ investment \cdot 2years - cost\ of\ investment) \cdot 100\%}{Cost\ of\ investment} \quad (4.6)$$

$$ROI = \frac{(30988 - 27300€) \cdot 100\%}{27300€} \cong 13{,}5\% \quad (4.7)$$

5 DESIGNED IOT SYSTEM VALIDATION AND DEPLOYMENT

Despite of the fact, that calculations stated high feasibility of the investments for building an IoT system. Although, our plant management decided to test the idea for having solid proof that it will give us the needed information for preventive actions and future improvements.

5.1 Framework validation

In order to prove it, the author of the thesis decided to test air flow meters for capacity measures and see how this data can be helpful for predicting failures and organizing preventive actions. Flow meter test was also chosen because it gives results about one of the main parameter about air compressor, as capacity. And it is the most expensive from sensors, what are planned to install for designed IoT system.

The aim of the test is to measure current compressor park machines output capacity and compare it with factory data to evaluate the wear of the screw element. This test should show us what compressors screw element is in the worst condition and/if some actions can be done from the data.

Test was performed with ***MesseTechnik VA300*** [21] portable air flow measuring device and it works with heated probe principle. Test duration on each machine was 25 minutes, time counting started when machine reached its normal operation temperature, 80 degrees.

Table 5.1 Capacity test results

	#	Brand	Model/Year	Factory capacity [m3/min]	Measured capacity [m3/min]	Difference [m3/min]	Dif.%
Low Pressure System	1	Tamrotor	L 200 / 1994	36,3	35,2	1,1	3,0
	2	Tamrotor	L 200 / 1992	35,5	34,5	1	2,8
	3	Tamrotor	LG 200 / 1992	43,3	41,0	2,3	5,3
	4	Atlas-Copco	GA 250 7.5 / 1996	45,2	40,6	4,6	10,2
			LPS Total	**160,3**	**151,3**	**9**	**5,6**
High Pressure system	5	Tamrotor	FL 75 / 1996	12,2	11,7	0,5	4,1
	6	Tamrotor	FL 75 / 1996	12,2	11,0	1,2	9,8
	7	Atlas-Copco	GA 75 / 1999	14,1	13,9	0,2	1,4
	8	Garden Denver	ESD 90 / 2005	16,7	16,4	0,3	1,8
	9	Garden Denver	ESN 250 / 2008	43,4	42,9	0,5	1,2
			HPS Total	**98,6**	**95,9**	**2,7**	**2,7**
RED - Out of normal operational variation							

Further inspection of machines #5 and #6 showed us that transmission belts and discs from motor to screw element were worn and slipped under load, which caused inefficient compressor work. Worn components were replaced and re-measuring on capacity showed that differences were reduced to 1.5% and 1%, which is in allowed variation. With these actions we can confirm that provided IoT solution could be beneficial for preventive actions and repairs.

Thorough visual inspection was done to machines #3 and #4 to discover some equipment malfunctions, but nothing special were discovered. Since compressor #4 is main machine and works constantly, author decided to gather energy readings from last 6 months (September 2016-March 2017). Data was formulated to graph to discover any significant changes over the time period what could show us some disturbance in trend.

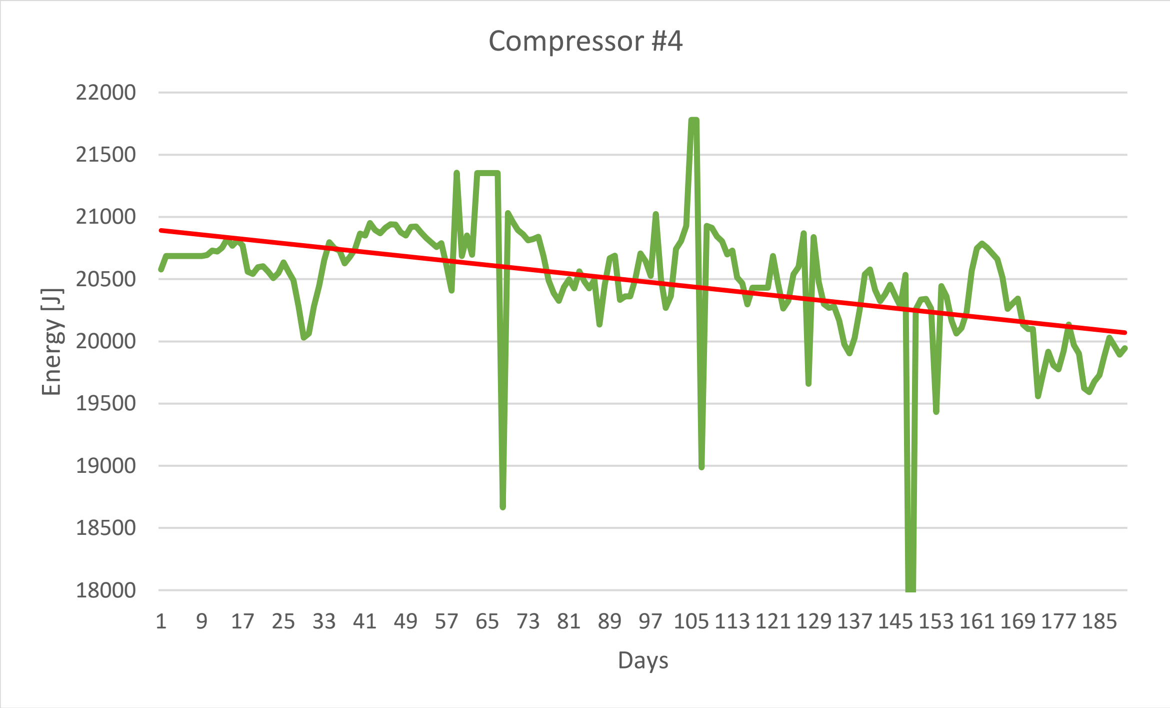

Figure 5.1 Compressor #4 energy readings

From compressor #4 energy graph (Figure 5.1) it can be clearly seen that general energy consumption has dropped over the time and it can be linked with worn-out screw. Possible cause could be that screw elements are worn and consumes less rotational power to produce less air at lower pressure. This explanation goes well together with our capacity readings as well.

As compressor #3 is mostly in rest mode for backing up system if needed, it does not have enough energy data to compare, what could link with capacity reduction as root cause. Further on, author ordered vibration analyses from external company to measure both machines for vibrations. As mechanical vibration is clear sign of physical wear, it can be linked to screw wear and approve our capacity measurement results.
Vibration analyse report from contractor showed that current situation in both machine screws are over the normal operation parameters, what are stated in ISO 10816-3:2009 [22] standard. Results were **2.1%** over nominal for compressor #4 and **3.8%** over nominal vibration for compressor #3.
In order to fix previously found problems with compressors #3 and #4 were asked quotations from original supplier for screw overhauling. It turned out that fixing cost for both machines were roughly 23k and 27k euros, what is half of the price of new same size compressor. Fixing cost is high, because they are both out of production model as they are old and need custom made spare parts.

In correlation of capacity and energy analyses came out interesting matter what is related to low pressure system total capacity and production variation. Issue can occur if all production lines will be occupied with large containers and LPS is running with all compressors. Problem stands in the question, is the LPS capacity big enough to tolerate any compressor failures in this kind occasion. This matter could be source for further FTA analyses for risk management and investment planning. FTA analyses will not be conducted in this thesis, since it will go out of the scope of this thesis, thus this problem can be source for further analyses in some other project/thesis.

The test revealed the poor condition of our four compressors, where two of them were repairable with reasonable cost and other two were not. As a result of this test, our management decided to invest into two new modern compressors what has already IoT integration capability to raise the system reliability and efficiency by detection and preventive actions. Additionally, was replaced LPS multipilot system with newer and modern one, also with IoT integration possibilities.
This test proved to our management that this kind of new approach in Järvakandi O-I plant will be beneficial for reliability wise and they decided to continue implementing this framework with provided solution to collect further data in order to improve.

5.2 IoT deployment in compressed air system

Previous sub-chapter help to validate the idea of developing IoT based system is beneficial to our enterprise. Infatuated to that, our company is thriving forward to this direction by taking step-by-step actions.

Due to problems what were discovered in framework validation phase, were replaced two old compressors GA 250 and LG200, from low pressure system to new modern ones. These new Atlas Copco GA200 (Figure 5.2) compressors have already installed gateway connection to internal network for cloud monitoring. It allows to see machine's operations, but do not record it to internal cloud.

Figure 5.2 Atlas Copco GA 200 interface with IoT integration

Together with compressors was installed also new ES6 Atlas Copco (Figure 5.3) multipilot system what is connected with all LPS machines. ES6 has again network gateway connection and with that can be observed the system operation, but no recording is done to internal server for further analyses.

Figure 5.3 Atlas Copco ES6 multipilot

As the first step of deploying developed IoT framework, were creating cloud server for data recording. With this action we can start recording data from installed equipment, as compressors and multipilot, and it also allows to immediately start data recording if we install any additional measuring equipment. When analytics and visualization software will have developed, we can start feeding recorded data into it from the cloud server.

Next step was installation of four pressure sensors with digital display (Figure 5.4) to forming machines LPS feeding pipes. Purpose of the sensors is to gather data about pressure fluctuations in this area. Measuring data is recorded to cloud server for further analyses related to problem covered in point number 7 at

Table 4.3.

Figure 5.4 Pressure sensors on forming machines LPS feed pipes

The next steps will be analytics/visualization software development and deployment for further actions in order to make improvements. There on would be installation of other missing components from designed IoT frame. As they are flow meters, pressure and vibration sensors.

Current situation with the deployment is visualized on Figure 5.5, where already accomplished works are surrounded with red frames.

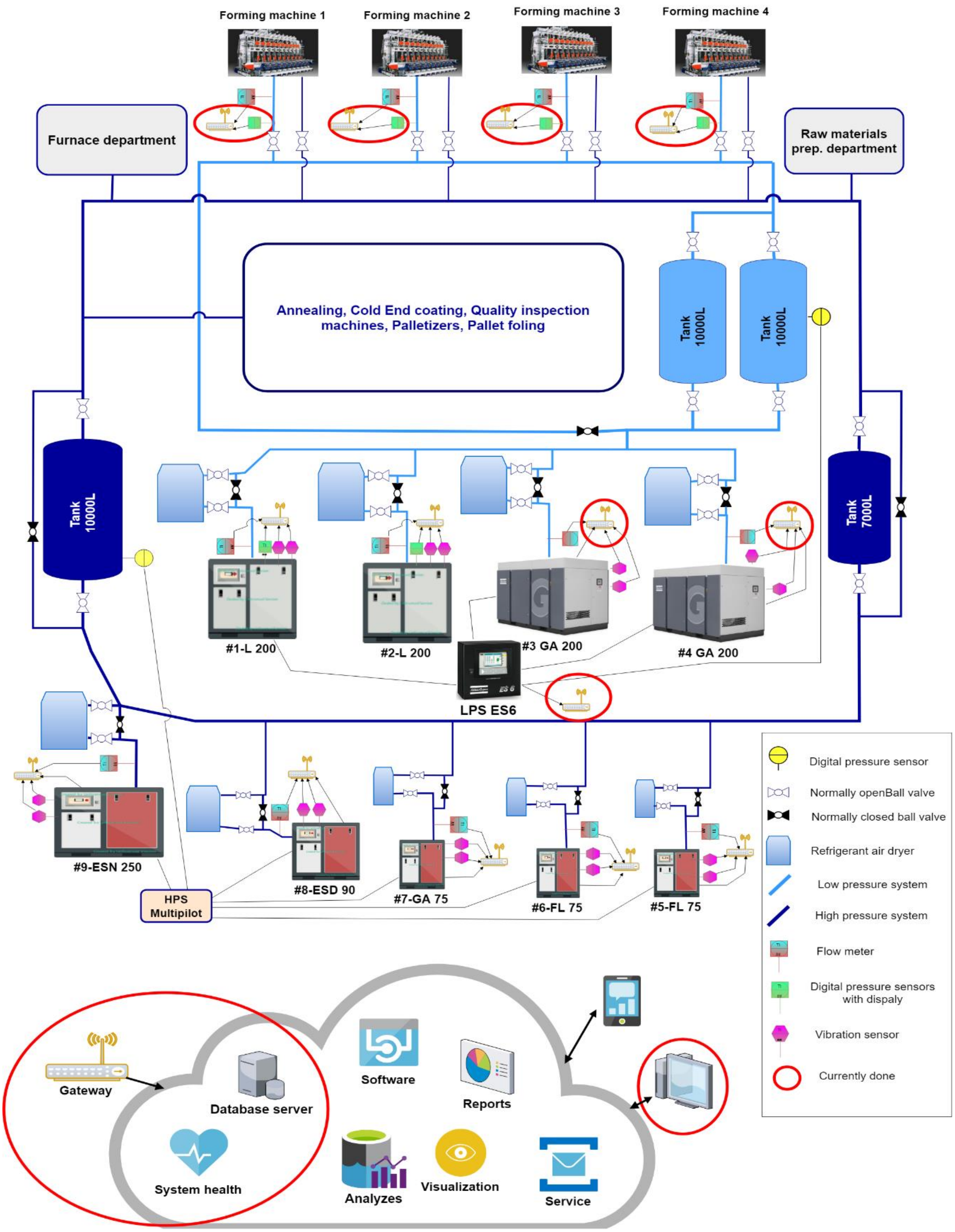

Figure 5.5 Current IoT deployment state

SUMMARY

The purpose of this master thesis was to develop an IoT based framework in order to design and built IoT infrastructure for managing compressed air system. Thesis topic was raised from the issue of compressed air system reliability, what is causing production losses and instability in general efficiency of the plant. The aim of new IoT system is to observe the compressed air system in order to plan preventive actions for avoidance of major failures and to stop acting as "*extinguishing the fire*". Additionally, to start gathering data about the system, on based what could improvement actions developed and deployed in the plant.

In the introductory part of the thesis, the author gives an overview of what is happening in glass container industry to better understand why company is moving forward to implementing Industry 4.0 and IoT ideology's in sight of improvements. Shortly is explained they logic behind the plant core functions and the criticality of support systems.

In order to fulfil the main task of the thesis, thorough literature review was conducted for fully understand the scope of main thesis objective. Literature review is covering the latest dynamics in industry as they are Industry 4.0 and IoT ideologies together with Lean Six Sigma, also are explained five most common tools for reliability engineering for purpose to select most suitable one for the IoT framework development.

Following task was to develop a framework for designing an IoT based infrastructure in order to manage compressed air system. Framework is developed with keeping in mind Industry 4.0, IoT and Lean Six Sigma basics, together with reliability engineering tool FMEA, what helps to define most critical points for IoT integration for data collection in order to take action preventively or for improvements. As in this thesis, this framework is used for managing compressed air systems with IoT integration, as well it can be used with any other kind of systems where is desired reliability gain trough IoT integration.

Prior of using developed framework for designing an IoT system, author of the thesis gave a brief overview of O-I Production Estonia AS and visualised with explanations the main production processes for understanding how compressed air driven everything is. Detailed description of previous compressed air system together with visualised schema was provided to have a clear understanding of the system. Further on were conducted team based FMEA analyses to define base RPN number for marked failure modes. Improvement actions were offered together with the team and new RPN’s were calculated in order to compare them with old ones. As a result RNS’s were improved from 25-95% on specific failure modes, it confirmed that planned IoT system will be beneficial for reducing risks in system. Improvement actions from FMEA were used for carrying out survey about compressors in order to design IoT system with external contractors.

The last task of the thesis was to validate developed framework and prove to the plant management that provided IoT system will be beneficial as it raises compressed air system reliability. In this part, author conducted a test, where was discovered that 4 out of 9 compressors had some problems with main function and needed repairs. Performed test validated framework fully as is gave desired data in order to take preventive actions and plan investment. Conclusion was drawn by the management as well, to continue deployment of designed IoT system with step-by-step actions.

In conclusion, author of the thesis is very satisfied with the outcome, as the developed framework were validated well in the conducted test, what additionally proved to our management to continue with IoT integration bath. Moreover, from here raises many topics for further research as in the plant are several other critical support systems such as vacuum and raw water, where an IoT integration can raise the reliability and safety in the plant.

KOKKUVÕTE

Antud magistritöö eesmärk oli arendada raamistik, mille abil on võimalik disainida ja arendada välja IoT-l põhinev juhtimis ning jälgimis süsteem suruõhule. Magistritöö teema arenes välja suruõhu süsteemi problemidest ja ebastabiilsustes tulenevalt riketest, mis põhjustavad tootmise seisakuid ning üleüldist effektiivsuse langust. Uue arendatavad IoT infrastruktuuri eesmärk on alustada suruõhu süsteemis ennetavate tegevuste tegemist, et vältida rikkeid ning mitte päästa olukorda, kui see on juba juhtunud. Teiseks eemärgiks oleks olekuinfo kogumine, mis võimaldaks viia läbi analüüse süsteemi parendamiseks ning nende planeerimiseks.

Sissejuhatavas osas autor annab ülevaate hetkel klaaskonteinerite turul toimuvast, mis selgitab miks ettevõte on otustanud rakendada enda tootmises Tööstus 4.0 ja IoT ideloogiaid. Lühidalt on kirjeldatud ka tehase põhisüsteemide loogika ning opereerimine kui tervik süsteem.
Magistritöö püstitatud eesmärgi täitmiseks, viis autor läbi põhjaliku kirjanduse uurimuse, et mõista terve töö temaatikat ja teooria arusaamu. Kirjanduse valik hõlmab Tööstus 4.0, IoT ja Lean Six Sigma ideoloogiad. Lisaks uuriti ka viite enimlevinud tehnika usaldusväärsuse arendamise töörista, mille seast valiti välja kõige sobilikum töö tarvis.

Järgnev ülesanne oli arendada sobilik raamistik IoT süsteemi disainimiseks, et hallata suruõhu süsteemi. Raamistiku arendamisel on jälgiti Tööstus 4.0, IoT ja Lean Six Sigma põhialuseid koos süsteemide usaldusväärsuse disainimise tööriistaga. Eelnimetatud tööriist aitab defineerida kõige kriitilisemaid seadmete parameetreid, mida integreerida IoT jälgimissüsteemi, mis võimaldab planeerida tegevusi ennetavalt. Kuigi selles töös kasutatkse arendatud raamistikku ainult suruõhu süsteemi haldamiseks IoT võimalustega, siis lisaks on seda võimalik rakendada kõikide tehniliste süsteemide puhul, kus soovitakse selle usaldusväärsust tõsta.

Enne arendatud raamistiku kasutamist, annab autor ülevaate O-I Production Estonia AS-st ja selle põhilistest tootmise funktsioonidest. Lisaks selgitab selle juurde kus ja kuidas need on seotud suruõhusüsteemidega. Peatükis on samuti põhjalik suruõhusüsteemi kirjeldus koos visualiseeriva skeemiga. Järgnevalt viidi läbi arendatud raamistiku rakendamine, kus siis tehtid FMEA analüüs koos meeskonnaga, et määrata esialgsed riski hinded. Järgnevalt leiti koos meeksonnaga soovitatavad parendustegevust, mille põhjal arvutati välja uued riski hinded ning võrreldi algseteks, et leida nende effektiivsus. Tulemusena vähenesid rikete riskid 25-95%, mis tõestas planeeritava IoT süsteemi kasulikkust. Parendustegevused FMEA analüüsist oli aluseks planeeritava IoT süsteemi disainimiseks ning nende põhjal arendati koostöös väliste ettevõtetega välja sobilik IoT lahendus.

Magistritöö viimaseks ülesandeks oli valideerida raamistik ja põhjendada ettevõtte juhatusele, miks pakutud IoT lahendus on neile kasulik. Eelnimetatud ülessannete täitmiseks viis autor läbi testi, mille käigus avastati neljal kompressoril üheksast vead kruvielemendi tööga, mis vajasid parandusi. Avastatud probleemid analüüsiti põhjalikud, et kinitatada nende tõesust, mis ka suudeti. Läbiviidud test valideeris täielikult arendatud raamistiku, kuna võimaldas saada infot ennetavateks tegevusteks ja tuleviku investeeringuteks. Samuti, ettevõtte juhtkond otustas testi tulemuste põhjal edasi liikuda pakutud IoT süsteemi rakendamisega.

Kokkuvõttes on autor väga rahul antud magistirtööst saadud tulemustega, kuna läbiviidud testiga suudeti positiivselt valideerida arendatud raamistik. Ning see omakorda aitas veenda ettevõtte juhtkonda IoT põhiste süsteemide arendamise poolt, et vähendada ettevõtlusrikse. See omakorda tõstatab ainest edasiseks uurimiseks, kuna tehases on veel plaju teisigi põhiprotsesse toetavaid süsteeme, kus oleks suureks kasuks IoT lahendustest riskide vähendamisel.

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