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Demonstration of real-time criticality assessment using a test-bed

Dynamic maintenance prioritisation based on criticality assessment of real-time production data with help of a Computerised Maintenance Management System

Master Thesis in Production Engineering

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Abstract

Maintenance is an important part of industrial operations. Companies worldwide used various methods to plan and execute maintenance activities, criticality classification of assets is one such method. Traditionally, criticality is a fixed value but thanks to IoT in industry, there is a possibility to gather real-time data to analyse criticality of equipment dynamically to carry out necessary maintenance. The purpose of this thesis is to formulate a method for assessing dynamic criticality for different assets with further classification of the criticality into important domains for planning dynamic maintenance activities. This is done using real-time system data and tested on a test-bed.

An extensive review of literature was conducted and a demonstrator test-bed was designed and built to demonstrate the project work. Data collection system and computerised maintenance management system (CMMS) software were provided by Axxos and IFS respectively. The CMMS uses a dynamic criticality method based on a multi criteria decision making model widely used in criticality rankings with an additional information on further criticality classification in so-called domains. The data obtained from demonstration directly relates to the criteria for obtaining criticality and impacts the variation in criticality of assets. Moreover, using this data, maintenance activities can be planned accordingly.

With use of real-time data, it is possible to have a clear information on status of system. The changing criticality of assets on dynamic level with help of computerised maintenance management system helps to focus maintenance resources on necessary assets, saving time and maintenance related costs.

Key words: Maintenance, Dynamic Criticality, Real-time Data, CMMS, Demonstrator, test-bed.

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Omkar Salunkhe & Patricia Quijada Fumero

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Terminology

AHP	- Analytical Hierarchical Process
CMMS	- Computerised Maintenance Management System
DAIMP	- Data Analytics in Maintenance Planning
FD	- Failure Detectability
FE	- Failure Effect
FP	- Failure Probability
EAM	- Enterprise asset management
ERP	- Equipment enterprise resource planning
FMECA	- Failure Mode Effect and Criticality Analysis
HMI	- Human Machine Interface
IoT	- Internet of Things
MCDM Models	- Multi Criteria Decision Making Models Things
MCCE	- Multi criterion Classification of Critical
MTBF	- Mean Time Between Failures
MTTR	- Mean Time to Repair
PCM	- Profit Centred Maintenance
OEE	- Overall Equipment Effectiveness
PdM	- Predictive Maintenance
PM	- Preventive Maintenance
RPN	- Risk Priority Number
TOPSIS	-Technique for Order Preference by Similarity to Ideal Solution
TPM	- Total Productive Maintenance
UR	- Universal Robot

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1 Introduction

This section will present a brief background to the thesis subject area. The purpose and objectives for this thesis project are also explained. The research questions are also stated and explained in this section. Lastly, delimitations are listed to further define the scope of the thesis.

1.1 Background

During the last few decades the role of maintenance in industry has changed drastically, it is no more an inevitable part of production but a strategic concern for accomplishing business objectives (Kobbacy, 2008). With be beginning of digital transformation of manufacturing industry and initiatives like Industrie 4.0 have gaining substantial attention for create smart factories with high productivity, flexibility, robustness, and sustainability. Industries across various sectors are expecting substantial cost reductions (Reinhard, Jesper and Stefan, 2016). Due to use of internet of things in industry, there is a changing trend among industrial researchers to start using data to analyse criticality of equipment's in a holistic manner to carry out proper maintenance (Bevilacqua and Braglia, 2000). This is made possible by the computerized maintenance management systems. Maintenance will have a central role in enabling the digital transformation and instead of being a cost-driver, maintenance departments will take lead in fields like production data analytics, computerized decision support systems and continuous learning. With emergence of Industry 4.0 and similar concepts, it is now easier to collect data from production on real time basis which can be used to support data-driven decision makings for example data driven maintenance prioritisation (Gu, Jin and Ni, 2015). Maintenance is a key issue when trying to achieve an interrupted flow with few possible stoppages, which will lead to higher utilisation of machinery and reduced idle time (Johansson, 2009). Knowing that the average OEE in Swedish manufacturing industries is about 55%, it is ensured that down times can be reduced using preventive maintenance resulting in increased OEE (Gopalakrishnan, Skoogh and Laroque, 2013).

Traditionally preventive and prescriptive maintenance has been carried out using personal experience (Sheu and Lin, 2006), even in relatively recent trends such as condition-based maintenance. With digitization and availability of resources to collect, monitor and influence changes in a systems behaviours, There is a huge possibility of increasing productivity through better maintenance management.(Kumar *et al.*, 2013). Specifically, in case of maintenance there are various tools that can be used in collect and process data from the production for supporting decision making. One of such tools is called Computerised Maintenance Management System (CMMS) (Costa, Lopes and Machado, 2014). This thesis demonstrates the use of real time data from production and use it for dynamic maintenance prioritisation in an industrial environment with the help of a demonstrator.

1.2 Purpose

The purpose of this thesis is to demonstrate decision support for maintenance planning through the realisation of proper/necessary maintenance of critical machines. A huge amount of available maintenance data is left unused (Gento, 2004), this data can be used to identify the critical machines in the system. Identification of critical machines is done on dynamic basis and with help of real-time production data to get a dynamic criticality classification.

1.3 Aim

The aim of this master thesis is to demonstrate a data driven decision support for maintenance prioritisation with the help of a demonstrator at the Chalmers Smart Industry lab. The aim is further formulated to answer following research questions.

RQ 1: How can real-time criticality assessment of assets be conducted to prioritise maintenance activities?

RQ 2: How machines can be classified based on their criticality using real-time production data?

The first research question address the use of real-time data for supporting dynamic criticality assessment of machines in an industrial environment. This demonstration is done with the help of a demonstrator. The criticality assessment of the machines is based on different criticality assessment methods investigated through a literature study of different methods used for analysis of production data for maintenance prioritisation and system optimisation. The aim is to identify a criticality assessment method that can be used to demonstrate dynamic classification of machines into different critical levels with the help of real-time data.

The second question will be addressed by demonstration of criticality analysis of a production system for maintenance prioritisation with the help of a demonstrator at the Chalmers Smart Industry Lab. The aim of this question is to use the methods investigated in first research questions to live demonstrate use of production data to prioritise maintenance activities based on the criticality of machines. In addition, a commercial CMMS software provided by IFS will be used for data analytics and demonstrations. Literature study is carried out on predictive maintenance methods and approaches and a best suitable method is selected for using with the CMMS software

1.4 Scope

The thesis focuses on investigating different methods for assessing criticality of machines at system as well as equipment level. More emphasis is given on the multi-criteria decision making models (MCDM) for criticality analysis for maintenance activities. Different maintenance strategies that can be used in a computerised maintenance management system are also assessed.

A short description of the production system used in demonstration is also included. A short introduction to Industrie 4.0 and Produktion 2030 concept is also presented. Back office used for maintenance planning is also demonstrated in this thesis.

1.5 Test-beds in Research

In the field of scientific research in industry, as it is proposed in the business-centred classification in (Moss and Atre, 2003) a demo prototype can be used to successfully show the vision and functionality to managers and customers. Demonstrators in form of testbeds have been used before in autonomous robotics (Riggs, Inanc and Zhang, 2010). This master thesis project is a part of an industrial project titled Data Analytics in Maintenance Planning at Chalmers University of Technology. It is important that the thesis work properly describes and explains the working of modern technology like IoT and CMMS used in the project. The use of demonstrator in thesis projects helps in understanding the working of this technology used. The demonstrator also acts as a tool for conducting research on methods used in the thesis project. More importantly, the purpose of the demonstrator is to support and showcase the results of the thesis work carried out.

1.6 Delimitations

Following are some of the delimitations:

- This thesis does not elaborate on the demonstrator communication systems and data storage.
- The MCDM models studied in this thesis are those which are used in the maintenance prioritisation.
- Detailed description of the IFS and Axxos systems is not provided in this thesis.

2 Methodology

This section describes the thesis work, it more specifically introduces the method followed during the thesis project work.

2.1 Research Strategy

A methodology implies a followed procedure to achieve a desired result(Jonker and Pennink, 2009). Since the prime objective of the thesis is to identify critical machines and demonstration of identification and display of these critical machines using a Computerized Maintenance Management System, As proposed by Borrego (Borrego, Douglas and Amelink, 2009) there is a possibility to use a mixed method that combines qualitative and quantitative approaches. A study based on mixed methods including gathering and analysing both qualitative and quantitative data simultaneously was followed based on the purpose of the thesis work.

Quantitative research was carried out to identify best suitable criticality assessment for identification of critical machines in the system used in this thesis project. Quantitative research included literature review of various methods and techniques. Qualitative research carried out in this thesis project is based on the stakeholder analysis carried on with various stakeholders involved in the projects. Qualitative research involved face-to-face interviews with different stakeholders for stakeholder analysis.

Methodology followed in the research project is inspired from Freivalds and Niebel (Freivalds and Niebel, 2014) method engineering approach. As main focus in methods engineering is on designing and developing workstations for production and constantly study the work environment to achieve improvements. The process of developing work stations is described in following 8 steps:

Step 1: Select Project
Problem definition of the project often characterised by a product facing technical, economic or human difficulties. E.g.: quality issues, high production costs, etc.

Step 2 – Get and Present Data
Data significant to the study is gathered and documented

Step 3 – Data Analysis
Data gathered in pervious step is analysed in detail. Focus is on operations considered as waste. Improvement potentials are identified in this step.

Step 4 – Develop Ideal Method
Ideal method is developed for previously specified operations. Safety and productivity are taken into consideration.

<u>Step 5 – Present and Install Method</u>
The newly developed method is presented to managers and employees responsible for the concern operations.

<u>Step 6 – Development of Job Analysis</u>
Ensure that the staff is well trained and prepared for the job.

<u>Step 7 – Establish Time Standards</u>
The developed method is standardised in a reasonable way.

<u>Step 8 – Follow Up</u>
Follow up the method to verify improvements.

Research strategy followed in this thesis project developed by taking inspirations from above described model and based on the methodology proposed in(Jonker and Pennink, 2009) which considers methods as specific steps or actions to be followed during the thesis for answering the research questions. The developed method is as follows:

1. Thesis project plan
    a. Problem identification
    b. Project time plan
    c. Identification of stakeholders involved
    d. Identification of information resources

2. Project research instruments development
    a. Literature review
    b. Stakeholders interviews
    c. Design of demonstration

3. Data analysis and formulation
    a. Analysis of literature review
    b. Analysis of Stakeholder interviews
    c. Formulation of criticality assessment methods
    d. Finalizing design of demonstrator

4. Demonstration
    a. Demonstration of real-time production data collection
    b. Demonstration of real-time criticality assessment using a CMMS
    c. Demonstration of maintenance back-office

5. Results dissemination
    a. Results presentation
    b. Discussion
    c. Future scope
    d. Report

2.2 Literature Study

A literature review was done on the various of criticality assessment methods used for maintenance purposes. Major literature A logical order was followed by focusing on the purpose and research questions. Several scientific databases used to find suitable literature for the thesis project. Some of them are listed below:

- Chalmers University Library Database
- Google Scholar
- Web of Science
- Scopus

Some of the search strings and keywords used for searching literature are as follows:

- Maintenance
- Predictive Maintenance
- Maintenance + Productivity
- Criticality Assessment + Maintenance
- Computerised Maintenance Management System + CMMS
- Maintenance Management + CMMS
- Critical Machines Identification
- System Demonstrator
- Dynamic Maintenance
- Dynamic Maintenance + Maintenance Prioritisation

2.3 Stakeholder Interviews

A most common qualitative analysis methods used in research projects is interviews (Kothari, 2004). For stakeholder analysis, the question used in interviews are predetermined. The questions used in stakeholder's analysis were based on thesis project requirements like identification of requirements of stakeholders from the project. The scope of stakeholder involvement was also done using the stakeholder interviews. Concerning the thesis project work, stakeholders identified are as follows:

- Thesis project examiner: Researcher in DAIMP
- Thesis project supervisor: Researcher in DAIMP
- Data collection system provider
- Computerised Maintenance Management System provider.
- Thesis project members: Masters students and authors of this report

2.4 Data collection and Analysis

Data collection is very important considering the realistic reflection of reality (Bergman, Klefsjö and Holmbergs i Malmö), 2010). An interactive model proposed in (Miles, Huberman and Saldaña, 2013) has been followed for continuous data analysis. As the data collection and analysis part are continuous concerning the project work, the method proposed by (Miles, Huberman and Saldaña, 2013) suits the best for the thesis project work.

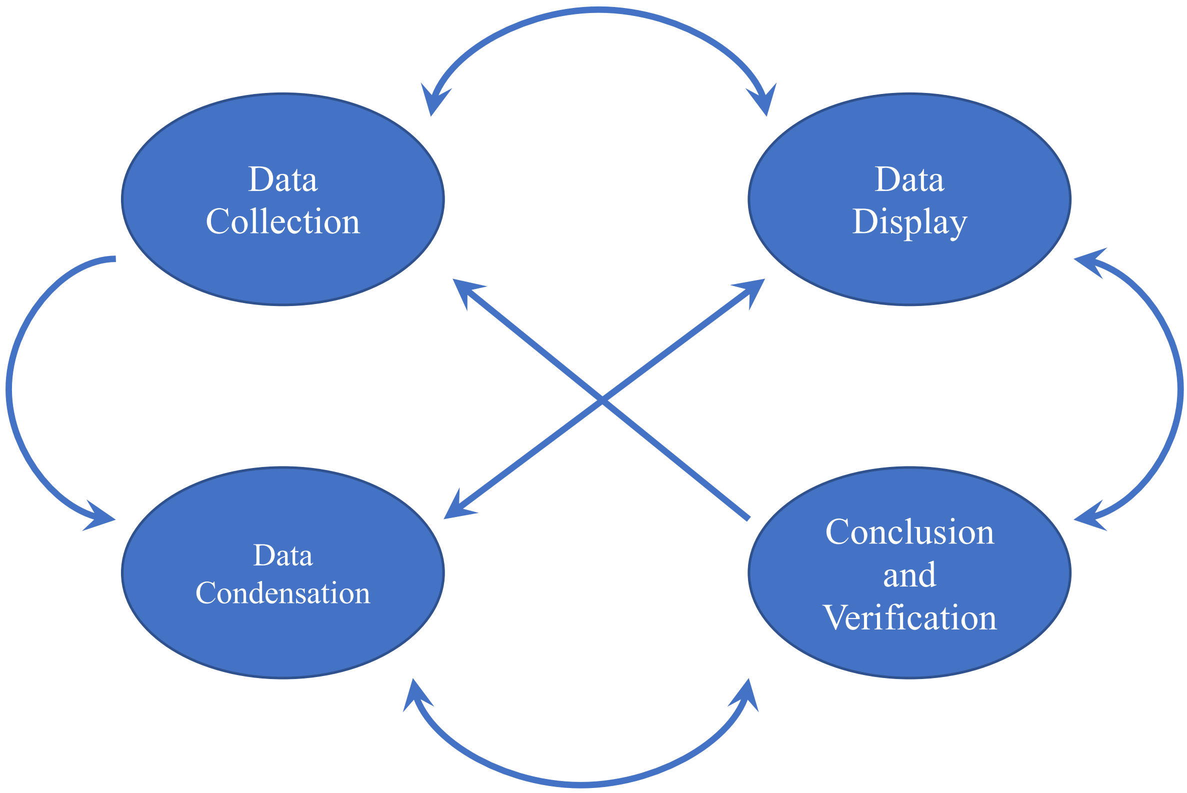

Figure 1: Components of Data Analysis-: Interactive Model

Data condensation as stated by Miles *et al* sorts, focus, sharpen, discards and organises data in such a way that final conclusions can be verified and drawn(Miles, Huberman and Saldaña, 2013). The process of finding, sorting and analysing quantitate and qualitative data in this project work needs the process of data condensation, specially the criticality analysis methods and data collection method for CMMS. Both these processes can generate huge amount of data, the above propose method will help in extracting the necessary data for the required results. The connection between data condensation and data display highlights the part of continuous data collection from the system and using that to display criticality assessment of the assets. The interrelations shown in the figure 1 show the process carried out in the project work. Data collected in condensed and used to display the results drawn from criticality assessment.

2.5 Ethical Issues

The thesis project work has been carried out within ethical bounds. Some of the aspects that have been considered are as follows.

- A reasonable amount of time is spent on thesis project work, especially in steps 2,3 and 4 in above mentioned method to obtain results that present an objective reflection of reality.
- Anonymity of all stakeholders is ensured as well as their permission to use all the information deducted or drawn from their activities or contributions.
- This thesis has been carried out in an academic environment. All the ethical rules and regulations of Chalmers University of Technology have been followed during the thesis project work.

3 Theoretical framework

In this section methods and techniques used in the thesis projects are explained. Research work conduced on the criticality analysis and different maintenance approaches used in industry are also presented in this section.

A holistic view of the evolution and current situation in criticality methods and CMMS was obtained via various scientific papers. The objective was to evaluate the present status of maintenance and its relationship with data analytics. Scopus and in Chalmers Library database were used as primary research database.

3.1 Project Background

This master thesis is a part of the research project titled Data Analytics in Maintenance Planning (DAIMP) at Chalmers University of Technology. The thesis works on the work package 5 of the research project with includes demonstrating use of a Computerised Maintenance Management System for planning and scheduling maintenance activities.

3.1.1 Industry 4.0 and Produktion 2030

Ever since the beginning of Industrialization, Changes and advancement in technology has led to paradigm shifts which we called industrial revolutions. field of mechanization (1^{st} industrial revolution), intensive use of electrical energy (2^{nd} industrial revolution), and the widespread digitalization (3^{rd} industrial revolution) (Lasi Hans-Georg Kemper *et al.*, 2014). Industry 4.0 by Germany and Produktion 2030 by Sweden are the latest trend of data exchange and automation in manufacturing field and which is been termed as the 4^{th} Industrial Revolution. These futuristic production systems contain very efficient manufacturing processes and characterizes scenarios in which the product controls its own manufacturing process by with extensive use of Internet and sensors, etc. and involves disciplines such as mechanical engineering, electrical engineering, computer science, business and information systems engineering. Some of the fundamental concepts used in Industry 4.0 are (Lasi Hans-Georg Kemper *et al.*, 2014)

- Smart Factory: Using “smart technology” to autonomously control the entire factory with use of sensors, actors, and autonomous systems in manufacturing.
- Cyber-Physical Systems: Production is connected with digital systems for continuous data collection and dynamic optimization.
- Self-Organization: Decentralization of existing manufacturing systems with decomposition of production hierarchy.
- New Systems in distribution and procurement: Development of products and services is individualized

- Adaptation to Human Needs: New systems are adapted to needs of workers and operators instead of the other way around.
- Corporate social responsibility: Industrial manufacturing processes are designed with focus on sustainability and resource efficiency.

It can be said that Industry 4.0 is IT Driven changes in manufacturing. These changes can be useful in increasing productivity, throughput and can be helpful in gaining financial benefits.

3.2 Maintenance Types and Concepts

For years, unexpected failures have resulted in significant production losses, disastrous safety hazards, costing substantially in repair or replacement. Thus, it is important to have a proper maintenance strategy to avoid these problems, but it is also important to have a proper maintenance strategy. A proper maintenance strategy will lead to reduced liked hood of equipment failure, increase in productivity and reduced downtime. A proper maintenance strategy will also result in reduced maintenance costs and higher product quality. While an improper maintenance strategy will cost the company dearly with cost and quality of products. There are several maintenance concepts listed in literature(Kobbacy, 2008), described below are some of the important maintenance approaches (Gento, 2004) found to be relevant for this thesis project.

3.2.1 Preventive Maintenance (PM)

Preventive maintenance concept was started in 1951. It used physical check-up of equipment method for preventing breakdown and prolonging of equipment life(Ahuja and Khamba, 2008). PM maintenance activities comprise of system overhauling and changing equipment spare parts. These pre-planned activities which are executed after specific time intervals for sustaining the process function. These activities are based on information like equipment requirement, time for execution, etc. Some activities in PM are performed during the process is up and running, and during setup change over. Some common PM activates are cleaning and replacement of parts, lubrication, adjustment and tightening(Ahuja and Khamba, 2008). Deteriorations signs on production equipment are also inspected during preventive maintenance activities. PM results in reduction of maintenance service level and downtime costs, and improvement of equipment's reliability (Pun et al., 2002).

3.2.2 Predictive Maintenance (PdM)

Predictive Maintenance is defined as "Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item" (SIS -

Industriteknik, 2001). PdM is based on equipment analysis, with focus on what needs to be done to sustain the function of the equipment. Historical data of systems behaviour is used to identify the different trends in the system. Based in this data, time of failure and different trends are detected accordingly. Equipment monitoring and inspection of equipment design can also be used for PdM activities. Another definition of PdM is “the use of modern measurement and signal processing methods to accurately predict and diagnose system condition during operation”(Shafiee, 2015). As the definition suggests, PdM activities and decision making is largely based on use of real time data and implies the current state of system and the use of technology to continuously monitoring the system is provide huge advantages in problem and potential failure detection.

3.2.3 Proactive Maintenance

Proactive Maintenance mainly deals with identifying and resolving specific maintenance problems(Gento, 2004). Proactive maintenance is a failure avoiding activity with prevents system degradation(Fitch, 1992). Proactive maintenance is mainly based on the machine system health. The machines are under observations for symptoms which can to performance degradation(Fitch, 1992). It should be noted that the proactive maintenance does not reacts to any failure condition but to the abnormalities and symptoms that occur before the failure(Fitch, 1992).

3.2.4 Total Productive Maintenance (TPM)

Total productive maintenance (TPM) is more than just a maintenance concept, TPM is also considered as philosophy adopted by many Japanese companies to fit their culture(Kobbacy, 2008). TPM involves total participation of all the departments of an organisation at all levels. TPM aims at establishing a thorough preventive maintenance system and maximising equipment effectiveness and fits in perfectly with the Just-In-Time (JIT) and Total Quality Management (TQM) approach (Kobbacy, 2008). TPM uses various tools and techniques like 6sigma, ABC analysis, fishbone diagram, 5S, SMED (single Minute Exchange of Die) Jidoka, poke yoke and OEE. All these tools are mainly used to integrate strengthen production, quality and maintenance issues(Kobbacy, 2008). TPM increases equipment reliability, productivity and maintainability(Pun et al., 2002).

3.2.5 Profit-Centred Maintenance

PCM stresses on the reduction of maintenance activities and for that purpose, it is focus on the re-engineering of maintenance practices by eliminating non-value-adding activities and reducing costs (Pun et al., 2002). So, the purpose of PCM is to increase profitability, centred in asset’s reliability and improving maintenance administration(Bond, 1997).

According to(Bond, 1997), the characteristics of PCM are: optimization process of maintenance function, reduction of maintenance cost by reducing the need of it, re-engineering of maintenance by eliminating non-valued adding activities and the use of maintenance personnel to effectively use maintenance-management information systems. Both (Pun et al., 2002) and (Bond, 1997) insist on use of maintenance information technologies as a key element of optimization that PCM proposes.

3.2.6 Reliability Centred Maintenance (RCM)

Reliability Centred Maintenance (RCM) is a method used for maintenance planning in which reliability is put in the centre. Four characteristics can be pointed out (Smith and Hinchcliffe, 2004):

- Preserve the function of the system
- Identify failure modes that could produce functional failure
- Prioritise the importance of failures modes
- Select effective PM tasks for the prior failure modes

So, it can be assumed that RCM is used to find maintenance requirements of any machine by taking care of its functions, the causes of failures and the effects of the causes on asset operations (Ahuja and Khamba, 2008).

3.3 Computerized Maintenance Management System (CMMS)

Manufacturing processes are designed to produced quality products at minimum costs and at high efficiency. With complex production systems, prioritization of maintenance becomes very complex and challenging(Gopalakrishnan *et al.*, 2015). With the beginning of Industrie 4.0 and Internet of things (IoT), there has been increase in system data collection which can be used for production optimization, maintenance planning or for economic reasons. This increased availability of system information and growing requirement of such data in real time for decision making gave rise to a Computerized Maintenance Management System. A CMMS is a tool that supports a maintenance strategy with the help of different set of functions that process data obtained from the system for producing indicators to support maintenance activities(Lopes *et al.*, 2016). As the maintenance process is supported by various resources, including equipment, availability of spare parts, personnel, and documentation, a CMMS helps in keeping track of these resources. CMMS is helpful in many ways, some of them are listed below(Rastegari and Mobin, 2016),

- Supports maintenance strategies implementation.
- Improved communication between maintenance personal and operators.
- Allows quick fault reporting by operators.
- Provides system information to maintenance managers for better decision making.
- Availability of historical data for developing preventive maintenance strategies.
- Tacking spare parts movements and location.

- Offers information on machines to make capital expenditure decisions.

Use of CMMS also facilitates implementation of Total Productive Maintenance (TPM) (Lopes *et al.*, 2016). The different functions of CMMS such as asset management, work orders management, preventive maintenance management, inventory control and report management allows effectiveness and efficiency in maintenance decision making process. A greatest misunderstanding of a CMMS is the belief of it being a maintenance strategy and not just a tool that supports the maintenance strategy. May times, poor usage of data along with wrong usage of tools leads to CMMS being just a “work order system” and lacks analysis and reporting(Wienker, Henderson and Volkerts, 2016). A CMMS needs to be supported by a proper IT infrastructure as it is the most critical setup of an CMMS. Successful integration of the new CMMS with the data collecting and information system is very important for the CMMS to work, one common requirement for this is the availability of fast internet and availability of information to every person across the organization. Many organizations struggle to implement CMMS, a very common reason is lack of interest from the senior management. Therefore, it is important that the senior management is made aware of the benefits of a CMMS and its ability to “convert data into information” and they take the lead in introducing CMMS throughout the organization. This should be supported by adequate resources and a proper change management process to avoid the resistance and failure of the implementation(Wienker, Henderson and Volkerts, 2016). Before starting the implementations, some important issues that should be addressed are:

- Clearly-defined guidelines for implementation.
- Clearly-defined roles & responsibilities within the organization.
- The need to work across the whole organization & not in units.
- The projection of realistic expectations of the changes & benefits that will occur from CMMS
- The understanding that resistance to change is normal and the provision of information/feedback opportunities to answer concerns.

A CMMS can calculate MTTR, MTBF, OEE etc. and provide reports that can help maintenance managers to quickly focus of the target areas and optimize use of resources for fault repairing and prevention. The quality of data is extremely important as the outcome of decisions made using this data is solely based on the accuracy of the data provided. Such action will lead to increase in productivity of the system and optimal use of resources. CMMS helps in facility management by in gathering data from various systems on daily basis and it is up to the facility managers and maintenance managers to use this data to improve the performance of the entire facility, while keeping it maintenance within the limited maintenance budget(Shalabi and Turkan, 2016).

3.4 Criticality Analysis

As per prior study, It has been observed that productivity can be increased by 5% thought strategic planning of maintenance activities (Gopalakrishnan *et al.*, 2015). This strategic planning of maintenance activities can be achieved by using criticality analysis of equipment. A machine/equipment which is very important considering with respect to the function is provides is given highest criticality. Prioritization can be based on the machines with highest criticality and are scheduled to be first while preforming maintenance activities. Criticality analysis is a process that provides systematic basis for determining priority of different assets within a maintenance management program, It also provides help in determining maintenance strategies which are used for different types of engineering assets like machines and equipment in production, manufacturing facilities, infrastructure and support systems (Crespo Márquez *et al.*, 2016).

There is a large amount of quantitate and qualitative techniques that can be found in literature which can be used for prioritizing machines/equipment for maintenance activities (Crespo Márquez *et al.*, 2016). Multi Criteria Decision Making Models (MCDM) are used to process this large amount of data to get optimal ranking of critical machines. These critical machines are based on based on frequency of failure occurrence, severity of failure effect and likelihood of detection during design and manufacturing.
Explained below are some methods we have used and referred for developing our own criticality method.

3.4.1 Failure Mode Effect and Criticality Analysis (FMECA)

One of the most common methods used in criticality analysis of system is FMECA with Reliability Centred Maintenance (RCM). FMECA provides a thought understanding of a systems failure behaviours. Many organisations have their own ways of using FMECA for specific purposes (Johnson, 2013).

The procedure consists on the detection of failure modes and its effect. Once they are detected, each effect is assigned a severity, occurrence and detection rate so, the Risk Priority Number (RPN) can be calculated as the multiplication of all factors.
It could be said that FMECA in one of the most popular techniques, though it has problems. Those problems are (Sachdeva, D. Kumar and Kumar, 2009):

- the dependence between failure mode and effect is not considered.
- the consideration of Severity, Occurrence and Detection as the only attributes.
- the way the Severity, Occurrence and Detection use the same measures. Also, the assumption that the same design level has the same values on different scales of the three index.
- Different combinations of Severity, Occurrence and Detection can lead to same

RPN.

- The way RPN is calculated

3.4.2 Analytical Hierarchical Process (AHP)

The Analytic Hierarchy Process (AHP) is a measurement theory which uses pairwise comparisons and relies on the judgements of experts to derive priority scale (Saaty, 2008). It is a multi-criteria decision-making approach which considers a top node (first level), criteria level (second level) and alternatives level (third level) (Ashraf, 1998). In this method, levels two and three are weighted as a function of their importance for the element that is beyond. Finally, criticality is based on Criticality Index which can be tested using the so-called Inconsistency Ratio (Sachdeva, P. Kumar and Kumar, 2009).

3.4.3 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is a multi-criteria decision making methodology based on the “measurement of the Euclidean distance of an alternative from an ideal goal” (Sachdeva, P. Kumar and Kumar, 2009), this means that the best solution should be as close as possible to so-called ideal solution and the farthest from so-called negative ideal solution. Different criteria are weighted and then, there is a mathematical method to systematically follow, the result is the Maintenance Criticality Index which is used to rank assets (Sachdeva, P. Kumar and Kumar, 2009).

3.4.4 Multi criterion Classification of Critical Equipment (MCCE)

MCCE is also based in interrelation of different factors. Criticality is obtained by using the so-called Criticality Index calculated using a systematic and detailed procedure explained in (Gómez De León Hijes and Cartagena, 2006).

3.4.5 Risk Assessment Techniques

The Risk Assessment Techniques consist on the calculation of Criticality Number, this number is used to do the criticality ranking using the probability of a failure with that severity occurring (Pelaez *et al.*, 1994). The Criticality resulted of the calculated risk is used in the CMMS for planning and scheduling maintenance purposes (Healy, 2006)

3.5 Use of Test-bed as Demonstrator

The demonstrator is based on the test-bed technology widely used in the industrial research. Scientists and engineers have been using simulations and test-beds for generating information and data for emulating manufacturing. Universities and research institutes are developing test-beds for research, development and testing of new methods and technologies. Automated Manufacturing Research Facility (AMRF) has developed a physical machining test-bed (Simpson, Hocken and Albus, 1982), UC Berkeley had also developed a test-bed for machining data analytics with MTConnect-enabled machine tool platform (Helu and Hedberg, 2015). With emergence of smart factories and availability of commercial tools for data collection and analytics like ERP systems and CMMS the importance of test-bed proves to be very important. Test-beds provide the cyber-physical infrastructure to ensure physical and computational elements for a system work together efficiently (Helu and Hedberg, 2015). At Chalmers Smart Industry Lab, this thesis project helps in developing a test-bed in form of a demonstrator system with is used for system data generation, data collection and analysis for criticality assessment.

4 Results

This section includes the result of stakeholder's interviews, a detailed explanation of demonstrator, the theory of developed method and the outcome method.

4.1 Stakeholder Analysis

Stakeholder analysis was conducted in the form of face-to-face unstructured interviews with different stakeholders involved in DAIMP project: two researchers and two companies were involved in the interviews. The interviews led to an understanding of the current situation of project, and the expectations of these stakeholders from the thesis project were also discussed.

The researchers have specific objectives from this thesis related to maintenance and more specifically, in decision support systems for production maintenance. By using a demonstrator, their express their interest in using real-gathered data to select key factors that led us into a good criticality classification. Their objective was to show it in a back office managed by maintenance personnel using the CMMS, which is provided by one of the IT system providing companies and would be able to calculate criticality dynamically and especially considering the bottleneck machine.

Role of the IT system providing is more about fulfilling the necessities for building the demonstrator system and setting up the CMMS. These companies are not looking for any specific findings, they have a support function and their requirements were related to parameters needed, system description and criticality method used.

All the interviewers have objectives in DAIMP project but, as far as this thesis project is concerned, the researchers have demonstrated clear goals related to maintenance while companies have not presented any specific goals.

Table 1: Stakeholder Analysis

DAIMP's stakeholder interests	
Researchers	**Companies**
Maintenance decision support systems	Use of test-bed
Use of test-bed	Design of test-bed
Real-time data for criticality assessment	Criticality assessment method used
Maintenance back-office with a CMMS	Data needed for criticality method

4.2 Demonstrator description

As mentioned before, DAIMP is an industry project so the demonstrator is the best way to show the companies and stakeholders the results obtained from real-time data in a real environment, rather than using a method based on experience.
The demonstrator has been designed considering the requirements from the research questions with focus on specific request from stakeholders and the facilities offered by CSI Lab for the development of the thesis.

4.2.1 Demonstrator design

The following is a graphic description of the system that it is explained below:

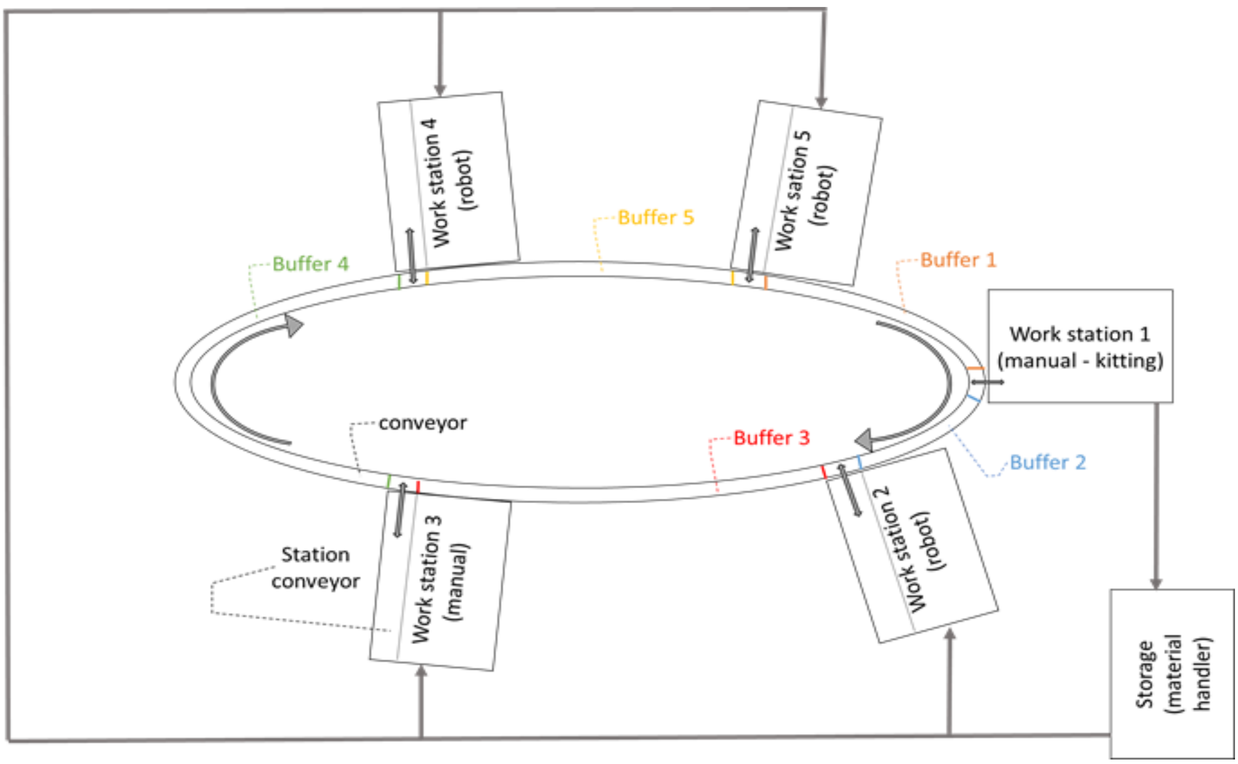

Figure 2: Description of demonstrator

The designed demonstrator will consist of five work stations. A storage managed by a material handler is also included whose task is explained later in the report. The value stream mapping of the product and material flow is as follows:

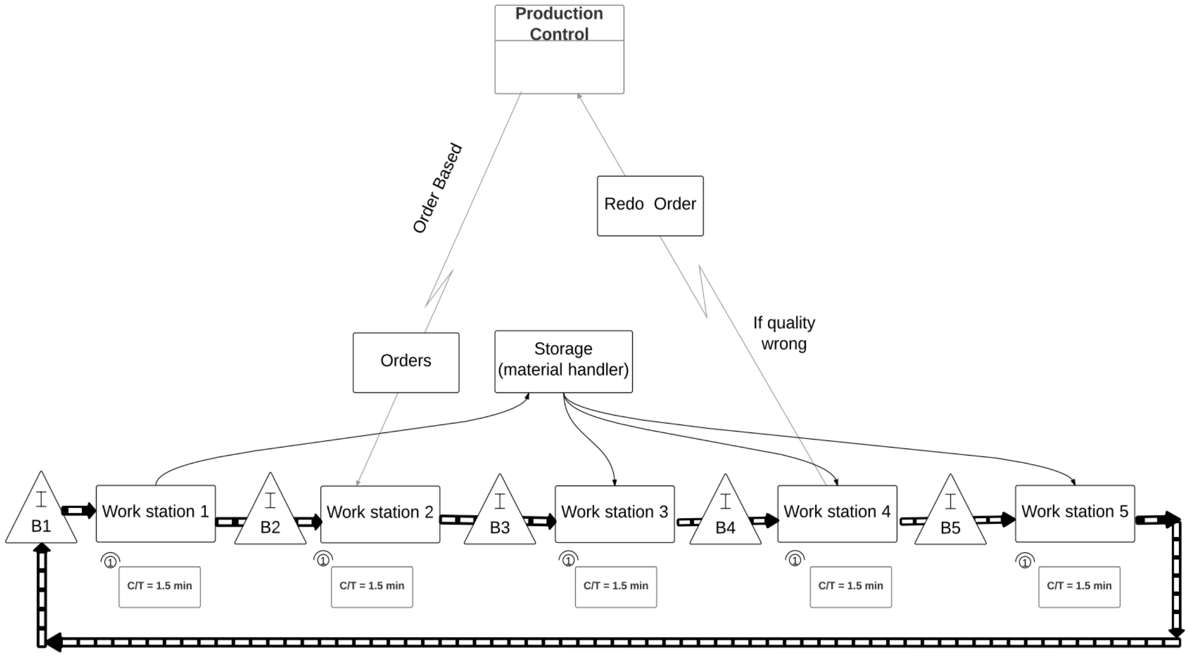

Figure 3: Value stream map of the production system

The idea is that the system is going to be order based, the orders are going to be electronically transferred to work station 2. In storage, a worker will be preparing and handle the parts needed in work stations 3, 4 and 5 by using Kanban system described later. Work station 2 uses a kit provided by work station 1, which is used for kitting and disassembling the product. The parts of the disassembled product will be placed in boxes that the material handler is going to take to classify and prepare the material needed for each station, the operator will retain the parts needed for kitting. As it can be seen in the VSM, it is a push system with buffers between stations, these buffers are to be placed in the conveyor by using a queue system.

The functioning product entry and exit for each station is the same as shown in figure 3 and figure 4. The assembly activities are different from station to station. Work stations 2, 4 and 5 have a robotic arm supervised by one operator, and work station 3 and 1 are manually managed by one operator each. All stations have small conveyor to bring the product to the work table and take away the finished product. These conveyor belts are connected to the central conveyor belt as shown in figure 1 that connects and controls the flow of material between each station. that acts like buffers by establishing queues before and after each station. The flow situations are:

Situation 1: the product enters in station. From “buffer i” from main conveyor, the product enters in “station i” by using the station conveyor when “situation 2 has happened:

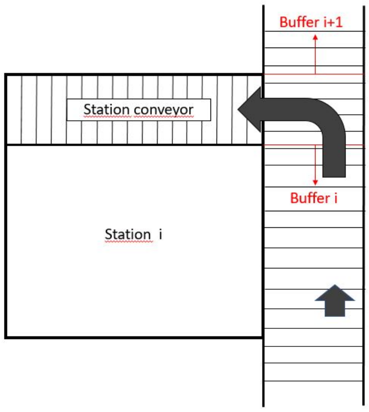

Figure 4: Visualisation of Situation 1

Situation 2: product goes out the station. Once the work is done, the product goes out the “station i” using the station conveyor to be incorporated into the “buffer i+1”. Now, “situation 1” can start:

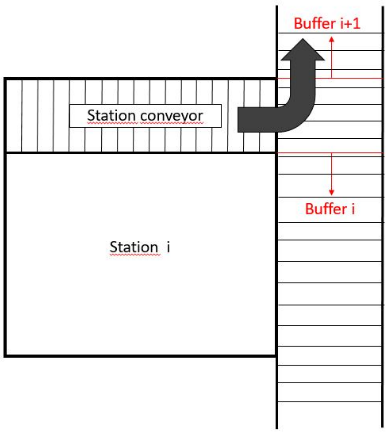

Figure 5: Visualisation of Situation 2

In work station 3, there are going to be two types of buffers, one for product A and a second for product B. The operator takes pieces depending on the product requirements to produce according to orders, instructions are going to be shown in a Human Machine Interface.

A quality check will be conducted done after work station 5. If the product is defective, it would continue to Buffer 5 to be disassembled, but the cause of failure should is to be detected and reported by the operator. As the order is considered to unfulfilled, it is electronically communicated to production planning and a new order will be communicated to Storage.

All stations will have a HMI display in which the operators could enter the cause of the failures of machines if they fail, these types of errors are:

- Wrong location of part to be picked by UR

- Robot program failure
- Robot error placing the part
- Big-buffer resulting in conveyor failure
- Station conveyor failure

Apart from the operators from the production system, a back-office manager and maintenance technician is needed in order to meet the research purposes.

The material handling is important in development of work as workstation 3,4 and 5. Martial handling will be required to have required levels of parts inventory on the workstation to fulfil the required tasks. The material handler is the responsible person to ensure that every stations is has the required stock for assembly. A material check round is planned every three to four minutes to restock (pick up empty boxes) every station. Each station will have a set of boxes (3x5, 2x7, etc.), the number of boxes will depend on the customer demand. In case of workstation 3, it will have 2x7 boxes for product with gear shaft A (Product A). The operator picks parts from the first set of boxes and when the parts run out, the empty boxes is then the signal to the “Kanban” system that they need to be picked up and refilled at the storage station by the material handler. Workstation 4 is a robot assembly with 2x3 boxes for Product A. The same “Kanban” signalling system is used on this station. The boxes will be restocked by the material handler similar to station 2.

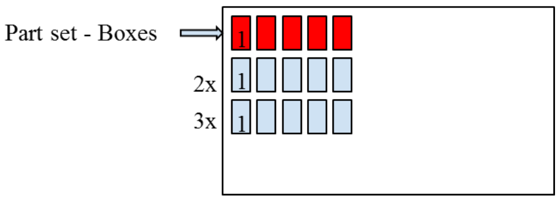

Figure 6: Kanban system at workstation 4

After a set number of products produced (in between 4-5) the boxes will be empty. Represented in the figure 5 as red boxes. This is the signal for the material handler during the material round to pick them up and move them to the storage for restocking. The empty boxes will be restocked with new material during the net material stocking round.

Every station consists of different operations as explained below:

Workstation 1: Kitting for Assembly / Disassembly

1. Pick and Place parts on pallet
2. Place pallet on conveyor
3. Start new work order

Workstation 2: Base Assembly - Robot Arm

1. Move pallet from conveyor to fixture on workstation

2. Start robot program
3. Working
4. Move pallet from workstation fixture back out on conveyor
5. Repeat for next product in buffer

Workstation 3: Gear Box/Engine Assembly - Manual (possible 3D-printer)

1. Get work order from ERP
2. Product arrives from conveyor
3. Built prod. A or B using workstation buffer and instructions.
4. Move Product From workstation to conveyor
5. Produce Product A or B to refill workstation supermarket buffer
6. Repeat when next product arrives from conveyor

Workstation 4: Assembly - Robot Arm

1. Product arrives from conveyor
2. Operator Pick and place parts from workstation inventory in fixture
3. Place pallet in fixture
4. Start correct robot program
5. Move pallet with product to conveyor
6. Repeat process

Workstation 5: Assembly - Robot Arm

1. Product arrives from conveyor
2. Operator Pick and place parts from workstation inventory in fixture
3. Place pallet in fixture
4. Start correct robot program
5. Move pallet with product to conveyor
6. Repeat process
7. Check quality
8. Send to disassembly

4.3 Data collection and CMMS

The data collection is one of the key elements of the master thesis. Data generated by the system can be used for system analysis, performance optimisation using shifting bottleneck method and for planning and scheduling maintenance. In this thesis project, we are focusing on dynamic prioritisation of maintenance activities using criticality analysis based on the system data. Each station in the production system is equipped with an HMI screen which are used for data collection. These screens provide the Axxos application with data on production activities, mainly producing time along with number of units produced, starvation on different station, blockage at the different stations and breakdowns in the system. Mean time to repair and time between failures is also collected. This raw data is processed by the Axxos application and simplified in a manner which is further used by the IFS application for criticality assessment of different machines and workstations. Following is the system data collected from different stations to be used in the thesis project.

Workstation 1: Kitting for Assembly / Disassembly
Active: Repairing, Setup, Working, Breakdown
Inactive: Waiting, Non-active

Workstation 2: Base Assembly - Robot Arm
Active: Repairing, Setup, Working, Breakdown
Inactive: Waiting, Non-active

Workstation 3: Assembly - Manual (possible 3D-printer)
Active: Repairing, Setup, Working, Breakdown
Inactive: Waiting, Non-active

Workstation 4: Assembly - Robot Arm
Active: Repairing, Setup, Working, Breakdown
Inactive: Waiting, Non-active

Workstation 5: Assembly- Robot Arm
Active: Repairing, Setup, Working, Breakdown
Inactive: Waiting, Non-active

Storage / Material Handling:
Number of parts

Buffers:
Number of buffers

Data for criticality assessment
Number of incidents (health, safety, environment), MTTR, cause of failure, spare parts needed for cause of failure, cost of spare parts, cost of man/h, cost of new equipment, MTBF, availability, failures per period, utilization factor, age, quality impact factor, number of unplanned maintenance interventions.

4.3.1 Axxos application

Axxos AB provides production monitoring system called Axxos OEE. This software is a tool that lets manufacturing companies monitor production on day-to-day, losses and potential improvements can be identified. This application can specifically collect data directly from stations, report downtime and scrap causes, register items and orders, present KPIs, visualize current situation of production, analyse current situation, be integrated in environment and improve production.

Concerning the thesis project work, the software is useful in terms of continuous data collection directly from the machines. The operators at each station can report any produced error and other system stoppages. The result is a database with information on the production operations performance. The Axxos system will be collecting data in form of active and inactive times at different stations, products produced, production hauls in terms of breakdown at work stations and/or product starvation at different work stations in the system. In addition, the Axxos system can calculate and display information on MTTR, MTBF, which is one of the primary requirements of this thesis project. Concerning the thesis project work Axxos OEE helps in the data collection.

The functioning of Axxos software is shown in following sketch:

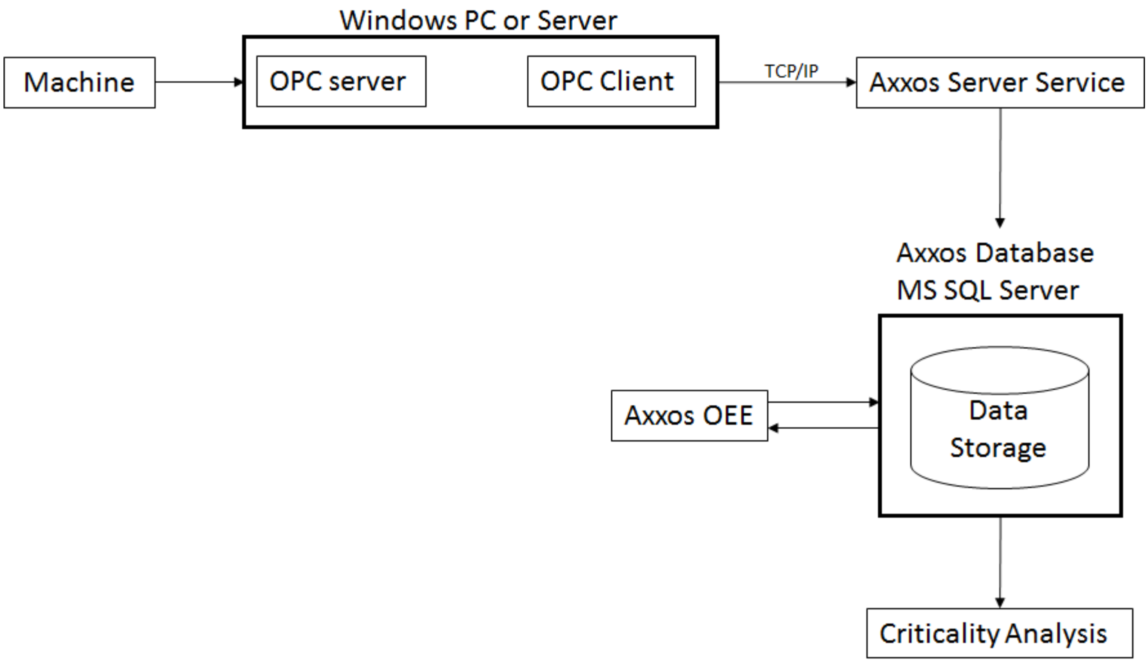

Figure 7: Functioning of Axxos Software

The data is collected from the work stations is in form of raw data. This is gathered at the OPC servers located near the production system. Axxos Data Storage imports data from the OPC servers and transforms it into different KPI's like MTTR and MTBF with help of Axxos OEE software and stored into the Axxos data storage. The excel sheet used into criticality method imports data from the Axxos data storage.

Table 12 show the data obtained from the Axxos servers. This data is gather on hourly basis. Appendix C shows the data obtained for 4 hours.

Table 2: Axxos Servers Data collection

MachineName	UtilizationFactor	MTTRinSeconds	MTBFinSeconds	NumberOfFailures
Station 1	0.73	162	518	5
Station 2	0.78	329	1342	2
Station 3	0.90	170	1470	2
Station 4	0.65	139	282	7

4.3.2 IFS software

IFS AB is a Swedish company providing industrial applications to enterprises thought-out the world. A commercial computerised maintenance management system (CMMS) application is provided by the company for analysis in this project. The application can provide detailed information on assets and their location along with the spare parts and costing in a detail. The application can be used to analyse the operational status of the entire system, functioning of different assets to name a few. The application capable of displaying critical assets. Entire maintenance information of the system is available with the application. The application can generate work orders for maintenance and these work orders can be assigned to specific maintenance personal. As the application is cloud based, the information can be accessed via internet. In this thesis project work, the application used to display critical assets along with the distribution of the criticality in different domains. In the application, ACME corresponds to Chalmers Smart Industry Lab. It must not be confused with another site.

The figure below shows an image of criticality number (master criticality) for robot 1 at station 1 with further classification of that criticality into 4 domains as displayed in the IFS application:

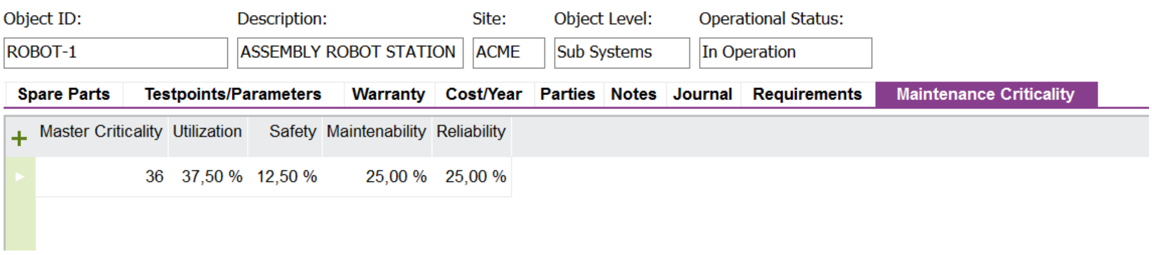

Figure 8: IFS Application

As shown in the above figure, the criticality of the all the assets in the system are updated every hour. Criticality of every asset per hour is shown in Appendix B.

4.4 Criticality assessment method

There are different approaches found while assessing criticality at different levels.
A common objective found in all methods was to rank the assets with respect to failure modes, rates, impact and consequences regarding their importance in the organisation

(Healy, 2006). Consequently, criticality assessment turns into an important tool in maintenance management (Crespo Márquez *et al.*, 2016). Considering the importance of criticality ranking in planning and scheduling, focus in on quantitative assessments (Healy, 2006) as it is based on data collection which is an important part in this thesis. There is also a need to properly select the criteria considered to keep the assessment workload within reasonable bounds (Healy, 2006). The literature points out different factors that are necessary to consider while conducting a criticality analysis since maintenance management carried out under the consideration of multiple factors (Labib, O'Connor and Williams, 1998). The more frequent factors used are as follows,

<u>Frequency of failures:</u>
It is related to the frequency with which a failure mode occurs. It is normally evaluated based on Mean Time Between Failures (MTBF). This type of data is gathered in historical records and maintenance logbooks but also, maintenance expertise is considered. (Sachdeva, Kumar and Kumar, 2008)

<u>Economic cost:</u>
Cost is not an easy factor as it must consider multiple variables and some of them are not in economic units. For that reason, quantities are usually assigned according to the expertise of maintenance personnel based essentially on production loss, spare parts costs and maintenance manpower.(Costa, Lopes and Machado, 2014)

<u>Spare parts:</u>
The availability and importance of spare parts in an asset have a considerable impact in any criticality method as there are plenty of them that are used when carrying out maintenance activities. (Sachdeva, Kumar and Kumar, 2008)

<u>Non-detection of failures:</u>
The chance of detecting a failure cause depends on the ability of maintenance personnel, the quality of periodical inspection or the reliability equipment diagnostic tools (such as alarms and sensors). (Sachdeva, P. Kumar and Kumar, 2009)

<u>Maintainability:</u>
It represents the easy at which an equipment is restored back to its up state so, the time frame taken is important as it could create a considerable impact in system (Sachdeva, P. Kumar and Kumar, 2009).

All these factors allow to monitor and control failures to collect data for carrying out maintenance activities. Along with the monitoring, it also creates data records about failures in the system. Ultimately, breakdown monitoring allows the calculation of a set of maintenance indicators: mean waiting time for repair (MWT), mean time between failures (MTBF), mean time to repair (MTTR), etc. these can be analysed for reducing number of failures and for planning and executing proper maintenance strategies (Sachdeva, P. Kumar and Kumar, 2009). Moreover, a back-office where data can be managed by a user with no database experience is supposed to be useful (Costa, Lopes and Machado, 2014). This tool is an interface in which the information about: assets, type of failures, spare parts, etc. is shown. It is an essential tool to support maintenance decisions (Costa, Lopes and Machado, 2014) and to offer a dynamic framework.The multi-criteria decision-making approaches are useful as maintenance involves multiple groups, it interacts with production, finance and quality aspects, among others (Labib, O'Connor and Williams, 1998). In the literature, some common approaches listed are: Analytical Hierarchical Process (AHP), technique for order preference by similarity to ideal solution (TOPSIS), Multi criterion Classification of Critical Equipment (MCCE) and Risk Assessment Techniques (Healy, 2006), these approaches are discussed in section 3.4 of this report.

An important finding from the study of these methods is that it is ensured that the literature provides a framework to decide the type of maintenance strategy according to asset's criticality. All of them are weighted scoring methods. AHP, MCCE and especially TOPSIS, are cumbersome considering the amount of calculations needed to be performed. For that reason, Risk Assessment Technique is preferred over other techniques, as the calculations are simpler. It also helps in developing a method which efficiently deal with the future research fields described in (Ylipää *et al.*, 2017). The method is able to:

- Identify of potential improvements
- use data collection for maintenance management
- create a dynamic framework for maintenance purposes
- create data-driven methods to ensure critical assets are available

4.4.1 Analysis of Literature Review

The literature study conducted in this thesis project helped in finding different criticality assessment methods. Each of these different methods had different criteria used for criticality assessment. The following table briefly summarizes the findings of each criticality method:

Table 3: MCDM model's comparison

	MCDM	Uses weighted criteria	Uses scales of rating	Mathematical complexity	Based on experience
AHP	x	x		x	x
TOPSIS	x	x		x	x
Risk Assessment	x		x		x
MCCE	x	x		x	x
FMECA	x		x		x

4.4.2 Developed Criticality Method

The method proposed goes far away from a classical A-B-C classification. The proposed method is going to be a dynamic analysis which considers multiple factors to obtain criticality classification that represents the current state of the production system. A better maintenance strategy can be carried out based on the criticality classification that will reduce the maintenance cost, prolong the service life of the equipment and improve production reliability and safety (Zhen Zhao, 2010). Also, maintenance approaches can be formulated according to real time requirements.

To achieve the ranking of machines according to criticality, the criticality number 'C' is going to be calculated. Prioritisation of the machines will be based on this criticality number. Higher the criticality number, higher the criticality. Criticality number is calculated using the following formula stated in Xia, 20014 (Xia, 2014):

Criticality = Failure Effect x Failure Probability x Failure Detectability ………...*formula 1*

A Risk Assessment Technique (Healy, 2006) is used to multiply risk (Failure Probability) and its effect (Failure Effect). The possibility and /or difficulty to detect the failure (Failure Detectability) is also considered. Higher the value of detectability (failure difficult to detect), higher the criticality.

A numerical value must be assigned to Failure Effect (FE), Failure Probability (FP) and Failure Detectability (FD). All of these parameters will be calculated by using different criteria's. Each parameter is explained below.

Failure Effect:

FE or failure impact: FE calculation is based on following criteria:

Operational impact: It is based on the Classification Method proposed in Bengtsson, 2011 (Bengtsson, 2011). Operational Impact is based on different scores that corresponds to different levels. Each asset will be in different level depending on the Classification:

Table 4: Operational Impact classification

Levels of Operational impact	Classification	Score
Extremely high	AAA	5
Very High	AA	4
High	A	3
Medium	B	2
Low	C	1

The data required for Classification Method calculations consists of utilization factor, age, quality impact factor. These factors are defined as follows:

Table 5: Utilization factor classification

Utilization Factor			
1	2	3	4
> 0.85	<=0.85 >=0.81	<0.81 >0.5	<=0.5

It is to be noted that the utilization factor will be dynamic in nature and it is an important factory in assessing dynamic criticality.

Table 6: Quality impact factor classification

Quality Impact Factor			
1	2	3	4
Extremely large tolerances for the machine type. Very large risk of customer impact	Very tight tolerances for the machine type. Large risk of customer impact	Normal tolerances for the machine type. Risk for customer impact.	Wide or no tolerances. No risk for customer impact

Table 7: Age Classification

Age			
1	2	3	4
>12 years	12-9 years	8-5 years	<5 years

The method considers the definition and values of these above-mentioned factors. The maintenance team uses the “assessment flow” to clarify which is the level of the machine (AAA, AA, A, B). The flow is graphically represented in the figure below.

Explanation of figure 6: In the following figure, the numeric values for utilization factor (U) are considers from table 3, quality impact factor (Q) considers values from table 4 and age (A) considers values from table 5. If a assets has utilization factor with values above 0.85 the corresponding criticality value is 1, according to the flow from figure 6, the machine is classified as “AA” critical. Similar procedure is followed for different criticality values until the assets is classified as in an critical classification.

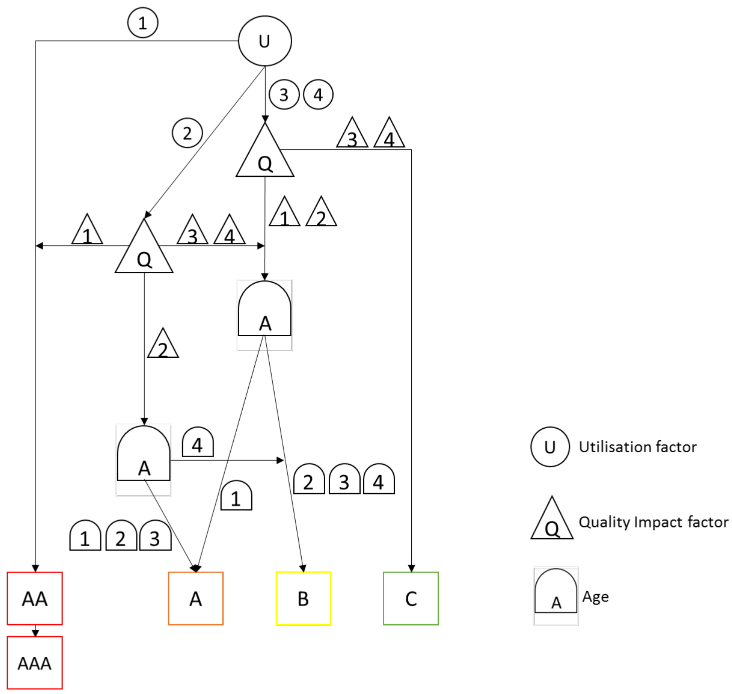

Figure 9: Assessment flow diagram for criticality

Safety: it is based on incidents produced related to health, environment or safety (Stenström *et al.*, 2013). Different levels and scores are used based on the number of incidents. The required data is number of incidents.

Table 8: Safety levels classification

Levels of safety	Number of incidents	Score
High	>=5	3
Medium	<5 >=2	2
Low	<2	1

NOTE: Limits of each level can be modified based on the number of incidents as per the need of the system/ maintenance organisation.

Maintainability (using the concept Operational reliability (Crespo Márquez *et al.*, 2016): it is based on measuring the potential impact of a functional loss to the system where the asset is installed taking into account the time needed to make it works again. The effects could be classified into different levels like having no effect, stopping the system less than x minutes (S < x), stopping the system more than x minutes (S > x), or leaving the system out of order. Data needed is MTTR (Kumar, 2014).

Table 9: Operational reliability classification

Level of operational reliability	MTTR	Score
System out of order	>6	4
Important effect	<=6 >=3	3
Effect	<3 >1	2
No effect	<1	1

Economic cost: Three categories are used in which the asset can be classified: high, medium, low with the score 3, 2 and 1, respectively; the intervals are going to be set according to economic limits of the company. For example:

Table 10: Economic cost classification

Level of economic cost	Economic cost	Score
High	x>€€	3
Medium	€<x<€€	2
Low	€ < x	1

To calculate the cost, required data is: cause of failure, spare parts needed for that cause of failure, MTTR, cost of the spare parts and cost of the maintenance personnel per hour. The economic cost is going to be calculated for each type of failure by using spare parts needed and MTTR, that are converted into monetary values by using spare parts cost and man-hour cost. "Cost of new equipment" is also included as a comparison is done between: "Maintenance repair cost and Cost of new equipment". The decision about what economic cost to be used in the classification (high, medium, low) is done as shown below:

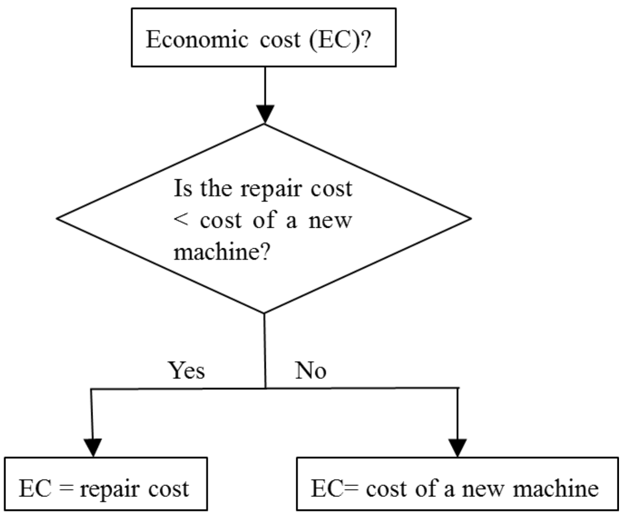

Figure 10: Economic cost calculation method

Operational reliability: the classification will be made using three levels (high, medium, low). The level for each asset can be calculated using MTBF or availability.

Table 11: Operational reliability levels

Level of operational reliability	MTBF	Score
High	<=4	3
Medium	>4 <=10	2
Low	>10	1

The Failure Effect (FE)= Operational Impact + Safety + Maintainability + Economic Cost + Operational Reliability

Failure Probability (FP):

(Crespo Márquez *et al.*, 2016) The only required criteria is "frequency of failures": the higher the level of failure, the higher the probability. By using the failures per time-period, classification of the frequency of failures in done in 4 levels:

Table 12: Failure frequency levels

Levels of frequency	Failures per time period	Score
Very high	>=10	4
High	<10 >=7	3
Medium	<7 >=3	2
Low	<3	1

NOTE: Limits can be modified if the number of failures are higher.

Failure Detectability (FD):

It is related to the simplicity or difficulty in detection of a fault or a failure. The criteria used is "detectability" further classified in four levels: undetectable (4), difficult to detect (3), detectable (2), easy to detect (1). According to the *formula 1* and levels shown in table 11, if the level of "detectability" increases, the criticality increases. If the purpose is to detect better or to know how difficult is to detect failures, to calculate the levels the parameter that we should use "Number of unplanned maintenance interventions" (Kumar, 2016).

Table 13: Unplanned maintenance levels

Levels of detectability	Number of unplanned maintenance interventions	Score
Undetectable	>=7	4
Difficult to detect	>7 >=5	3
Detectable	<5 >2	2
Easy to detect	<=2	1

By substituting all these values in the equation presented in *formula 1* a number for each asset can be obtained resulting in criticality ranking. Proposition is to rank the assets every hour so an evaluation of each assets criticality can be obtained along with a real representation of the current situation of the system status. Starting from a multi-criteria analysis, the proposed model converts relevant criteria impacting equipment criticality into a single score presenting the criticality level.

With a focus on multi criteria analysis, the method converts criteria into a score. This score is used to assess criticality (Crespo Márquez *et al.*, 2016), Higher the score, higher the criticality of the asset. As seen in different examples analyzed by Stadnicka (Stadnicka et al.2014), In industry the result is a criticality number and related to maintenance approach, but there is no information about why that particular machine or equipment is critical. In the proposed method, The criticality of machines/assets are defined from various different perspectives used in the method. Different domains like utilization factor, safety, maintainability and operational reliability are focused in this project. The developed criticality method will be able to identify an critical asset from one of the different domains listed above. Once the criticality number of each equipment is obtained, the criticality number is used to calculate the relative weights of each factor also called as domains (utilization factor, safety, maintainability and operational reliability). The maintenance personal will be able to focus on the required domains depending on the need of the critical asset. For example, if the machine is critical from utilization factor type of domain, attention will focus on that particular asset as the asset will impact the rate of production. Safety will always come first on the critical levels.

5 Discussions

In this chapter, the finding of thesis project work, the methods and results are discussed. Further uncertainties related to the thesis project work are brought up for discussion to explain and justify underlying arguments to final conclusions.

5.1 System and Data Collection

Due to time constrain, it was not possible to setup the highly-automated system described in the methodology where the automation was carried out by robots. The actual system consists of human worker also called as operators. These operators are assembling the exact same products in the exact same manner as the robots were tasked with assembling. Special care has been taken to avoid any deficiencies in data collection from the system. Every station is equipped with a HMI screens as shown in figure 10 below for providing better information.

Figure 11: HMI Screen

The screens are used to analyse the active and inactive time of each station, specifically, the systems status can be identified, like if the system is: blocked, producing, starved and error. Also, the number parts that have been produced can also be identified with the HMI screens. These times are controlled by the operator working on that station by switching buttons depending on current situation of the station. The screens provide the operator the capability to report errors and other information like lack of products. As far as the functioning of the system is concerned, data is gathered from each station using HMI, then goes to Axxos OPC in CSI Lab.

From there, it goes to Axxos virtual server in form of raw data. Data is stored in Axxos data base and it is filtered using Axxos OEE. The output is KPIs needed. These are exported to an Excel and from the Excel, to IFS application (CMMS), which is in so-called Back-office. Accordingly, the operating method is shown below in figure 11:

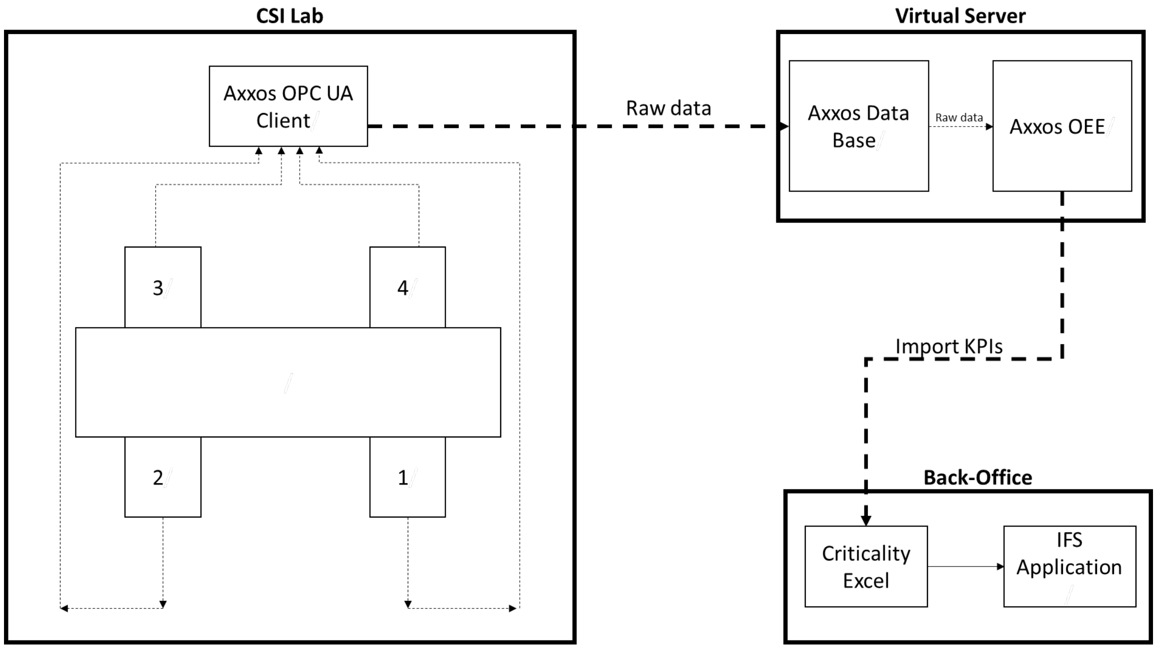

Figure 12: Data flow

5.2 Criticality Number Calculations

For criticality number calculations for different assets, an Excel sheet is developed to calculate criticality and the results are export directly to the IFS application. System data is imported to excel sheets using the Axxos Servers, as shown in the table 12 in result section earlier in this report.

Once the data for each robot is imported, it is automatically introduced into the tables that perform the calculations according to the developed method. These tables are introduced in the *data columns*. In each table, the Excel makes calculation for every criterion using the data and displays the result in *result columns*. For example, gathered information about “Robot 1” comes into “Data1” and “Data1” is used to calculate “Results1” by using a formula integrated in the Excel that is formulated according to the developed criticality method in section 4.3.2 in the results section. Following is the process described for robot 1, the remaining robots use exactly same process for their calculations:

- For Failure Effect (FE):

	ROBOTS INFORMATION								
Failure Effect		Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Operational Impact			4		4		5		4
	Utilization factor	0,73	3	0,78	3	0,90	1	0,65	3
	Quality Impact		3		3		3		3
	Age		4		4		4		4
Safety	*Nº incidents*	0	1	0	1	0	1	0	1
Maintenability	*MTTR*	162	2	329	3	170	2	139	2
Operational Reliability	*MTBF*	518	2	1342	1	1470	1	282	2

	ROBOTS			
	Robot1	Robot2	Robot3	Robot4
Calculations Operational Impact	C	C	AAA	C
	C	C	0	C
	C	C	0	C
	C	C	0	C
	C	C	0	C
	C	C	0	C
	0	0	0	0
	0	0	0	0
	0	0	0	0
	Result 1 C	Result2 C	Result3 AAA	Result4 C

Figure 13: Failure effect calculation

In the case of failure effect, quality impact and age are going to be fixed values, these values will be introduced manually in *result columns*. (In case of this project work, the values for age are fixed as the machines fall in the same criteria at the time of conducting practical's)

Once the results for every robot are obtained, the Operation Impact is calculated using the methods used by Bengtsson ((Bengtsson, 2011). The requirements according to the method are Utilisation Factor, Age and Quality Factor. Calculations are performed according to the flow diagram shown in as shown figure 6. In figure 12, the column titled "Calculations Operational Impact" is the result of the flow diagram shown in figure 6. The results are then used to calculate the result1 as shown in figure 12.

- For Failure Probability (FP):

The data required for failure probability is number of failures per hour and is directly imported from Axxos servers into the excel servers as shown in figure 13 below.

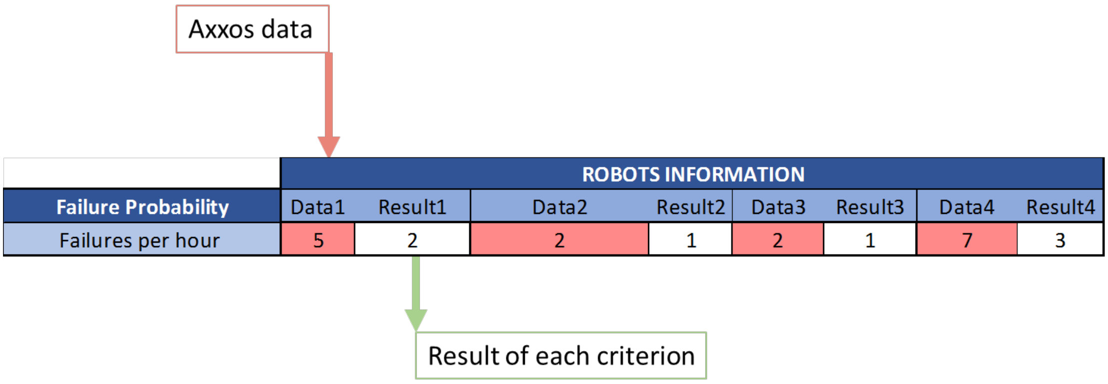

Figure 14: Failure probability calculation

For Failure Detectibly (FD), the values of the criterion are going to be fixed manually directly in *result columns*.

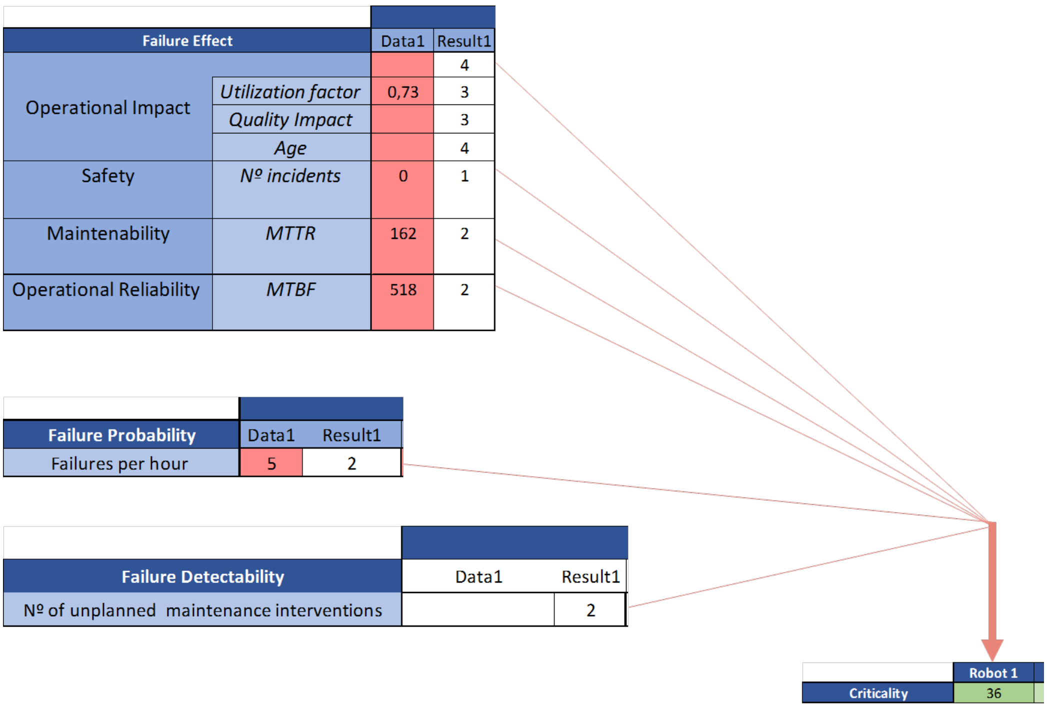

Figure 15: Criticality calculation

As the tables for FE, FP and FD are filled, criticality is calculated getting the results into the formula: *Criticality = Failure Effect x Failure Probability x Failure Detectability*, as it is shown below in figure 14 above.

As explained in the method, criticality criteria are also calculated by using relative weights of Utilisation Factor, Safety, Maintainability and Operational Reliability. Results of these criteria are used and calculations are shown in table 14 below.

Table 14: Further criticality classification into domains

	Robot 1	Robot 2	Robot 3	Robot 4
Criticality	36	18	18	54

Criticality Criteria	ASSETS			
	Robot 1	Robot 2	Robot 3	Robot 4
Utilization f.	37,50%	44,44%	55,56%	44,44%
Safety	12,50%	11,11%	11,11%	11,11%
Maintenability	25,00%	33,33%	22,22%	22,22%
O.Reliability	25,00%	11,11%	11,11%	22,22%

Due to time constrains it was not possible to include details and costing of spare parts. The cost factor mention in the developed methods has been excluded from the calculations due the fact that it mainly concerned with the cost of spare parts and repairs. As the thesis project mainly concerns with criticality calculations focusing on the utilization and operational impact of different assets with respect to the functioning of system like failures and repair times the cost factor has been left out of the focus area.

5.3 Dynamic Criticality and Maintenance Prioritisation

Effective use of different maintenance methods has resulted in increase in product quality and improvement in operational performance on production cycles ((Scipioni *et al.*, 2002). As per the result of analysis conducted by Selim *et al*, maintenance cost are problematic due to high deviation between planned maintenance costs and actual maintenance costs (Selim, Yunusoglu and Yılmaz Balaman, 2016). As proposed by various studies and industrial work, dynamic maintenance framework can be effectively used in manufacturing environments to provide repair, maintenance and overhaul service (Selim, Yunusoglu and Yılmaz Balaman, 2016) and can lead to cost saving in maintenance (Bouvard *et al.*, 2011). In this project work, the proposed criticality method will help in prioritising maintenance with respect to different domains. The data collection method used in thesis project work focuses on gathering important information of the production system which effects the behaviour and performance of different assets and the production system as whole. The results obtained using the proposed method provides information on not just the critical assets but this criticality is also sub-divided based on the four major domains that affect the performance of the assets and the systems as whole, namely utilization factor, safety, maintainability and reliability. The criticality of the assets is calculated based on this continuous data generated by the production system. The table below shows the criticality numbers obtained per station for four hours.

Table 15: Criticality per hour for different robots

	Robot 1	Robot 2	Robot 3	Robot 4
Criticality hour 1	36	18	18	54
Criticality hour 2	22	40	20	20
Criticality hour 3	20	22	36	18
Criticality hour 4	36	20	18	44

The maintenance personal will be able to dynamically prioritise the maintenance activities based on the different domains and the concerning asset from the production point of view. As maintenance strategies require proper schedule to achieve high system performance (Xia *et al.*, 2012). During the demonstration and data collection, maintenance time was added to the data collection system according to the critical machines. Based on the criticality of assets the maintenance personal can decide on the type of maintenance to be carried out. As shown in figure 15, it is to be noted that the criticality is changing per hour. This is due to the dynamic maintenance conducted on the critical machines. The data representation is result of dynamic maintenance simulation demonstration carried out for presenting the change in criticality of assets. The continuous updating of criticality of the assets will be helpful in effective scheduling of maintenance activities and will contribute to increased system performance.

5.4 Industrial Use

The developed method can use used in industrial application. The criticality assessment has been tested on a test-bed with help of an actual data collection system and CMMS, this method has a huge possibility of industrial application. The developed test-bed in generic in nature. Considering the production costs, Maintenance costs amount from 10% to 40% of the total production costs (Salonen and Deleryd, 2011). According to some figures these numbers can go from 15% to 70% of production costs (Salonen and Deleryd, 2011). With use of production data and criticality assessment of assets in maintenance planning, these costs can be brought down considerably. For example, Using the criticality assessment method, critical assets in the production can be identified. Priority maintenance in form of corrective as well as preventive maintenance can be carried out on these critical assets. The maintenance personal and resources will be used optimally on those assets which require maintenance reducing the costs on unnecessary maintenance. This maintenance will result in increase in performance and uptime of these assets resulting in increase in the production performance and bringing down the costs of maintenance. Based on the criticality of the asset, one of the maintenance type stated in section 3.2 can use used to plan and conduct maintenance on these assets. As shown in table 14, the asset is critical and the major reason for criticality is utilization factor. Preventive maintenance explained in section 3.2.1 can be used to identify and solve problems causing utilization factor and increase performance. Other maintenance types 3.2 like TPM and RCM explained in section 3.2.4 and 3.2.6 can be combined to perform maintenance if the asset is critical from safety or operation reliability. With continuous data collection and monitoring of the assets, based on historic data preventive maintenance can be carried on assets to avoid drop in performance of the assets.

6 Conclusion

This section summarizes the findings and the conclusions are presented by answering research questions.

RQ 1: How machines can be classified based on their criticality using real-time production data?

Real-time data collection creates an image of current situation while allowing to establish a base for decision making. Data mining has had an impact on the criticality of equipment which varies dynamically. In contrast with the process of traditional-fixed criticality assessment, criticality changes are registered with the system due to continuous collection of useful data with the help of different criteria used in the criticality method. This highlights the importance of quality in data collection to act efficiently in decision making by obtaining a criticality classification that reflects the reality.

RQ 2: How can we demonstrate use of real-time criticality assessment to prioritise maintenance activities?

With the latest technological advancement, there is a huge amount of data that can be gathered from a production system with respect to different parameters related to the assets in the system. It is up to the engineers to decide on up to what extent they will use it and for what purpose. As observed in the results, Real time criticality assessment is based on the behaviour of the different assets in the production system. The data generated helps in determining the actual condition of the system at given time. The number of failures and time to repair the breakdown gives insight in to the effect these failure cause on the entire system. Based on the criticality assessment of the assets and supported by classification of this criticality into different domains, the maintenance personal can easily prioritise the assets based on the criticality and its overall impact on the system. With the classification of the criticality into different domains, it is easier for the maintenance personal to prioritise the assets with minimum conflicts.

7 Further Research Possibilities

This section presents further research possibilities based on the thesis project work.

7.1 Demonstrator test-bed and CMMS

The demonstrator test-bed in very generic at the current stage. This can be further equipped with robots and sensors to acquire more accurate data. This test bed can be further used for further developing and testing the criticality model with industrial conditions Introducing higher level of automation can lead to different set of results. The criticality model developed is using excel sheet for calculations, but the CMMS application is capable of doing the same calculations efficiently. With direct integration of the data collection servers and CMMS application, the process of importing data from the servers to excel sheets and exporting it to the CMMS application can be completely abolished. Moreover, the maintenance back-office personal can only use the CMMS application for analysing and decision making process. With work orders directly generated from CMMS and information of spare parts and costs already available in the CMMS, more precis results including cost factor can be obtained.

7.2 Criticality Model

Criticality calculated in this thesis project is based on the system level with focus on each station with main purpose of maintenance prioritisation. The model can also be used to identify bottlenecks in the system. This can be further exploited by connect the model with different systems connected by the same flow of materials to analyse system and factory level performance. Cost factor has not been considered in the current research. This a good option to carry out further research on the working of criticality model.

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Appendix

Appendix A: Criticality calculations per hour in Excel sheet

First Hour

Failure Effect		Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Result 4
		ROBOTS INFORMATION							
Operational Impact			4		4		5		4
	Utilization factor	0.73	3	0.78	3	0.90	1	0.65	3
	Quality Impact		3		3		3		3
	Age		4		4		4		4
Safety	*Nº incidents*	0	1	0	1	0	1	0	1
Maintainability	*MTTR*	162	2	329	3	170	2	139	2
Operational Reliability	*MTBF*	518	2	1342	1	1470	1	282	2

Calculations Operational Impact	Robot 1		Robot 2		Robot 3		Robot 4	
	ROBOTS							
	C		C		AAA		C	
	C		C		0		C	
	C		C		0		C	
	C		C		0		C	
	C		C		0		C	
	C		C		0		C	
	0		0		0		0	
	0		0		0		0	
	0		0		0		0	
	Result 1	C	Result2	C	Result3	AAA	Result4	C

Failure Probability	Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Result 4
	ROBOTS INFORMATION							
Failures per hour	5	2	2	1	2	1	7	3

Failure Detectability	Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
	ROBOTS INFORMATION							
Nº of unplanned maintenance interventions		2		2		2		2

	Robot 1	Robot 2	Robot 3	Robot 4
Criticality	36	18	18	54

Criticality Criteria	ASSETS

	Robot 1	Robot 2	Robot 3	Robot 4
Utilization f.	37.50%	44.44%	55.56%	44.44%
Safety	12.50%	11.11%	11.11%	11.11%
Maintainability	25.00%	33.33%	22.22%	22.22%
O. Reliability	25.00%	11.11%	11.11%	22.22%

Second Hour

Failure Effect		ROBOTS INFORMATION							
		Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Result 4
Operational Impact			5		5		4		5
	Utilization factor	0.88	1	0.88	1	0.75	3	0.88	1
	Quality Impact		3		3		3		3
	Age		4		4		4		4
Safety	*Nº incidents*	0	1	0	1	0	1	0	1
Maintainability	*MTTR*	420	4	101	2	900	4	208	3
Operational Reliability	*MTBF*	3600	1	391	2	3600	1	2400	1

Calculations Operational Impact	ROBOTS			
	Robot1	Robot2	Robot3	Robot4
	AAA	AAA	C	AAA
	0	0	C	0
	0	0	C	0
	0	0	C	0
	0	0	C	0
	0	0	C	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	Result 1 AAA	Result2 AAA	Result3 C	Result4 AAA

Failure Probability	ROBOTS INFORMATION							
	Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Failures per hour	1	1	4	2	1	1	2	1

Failure Detectability	ROBOTS INFORMATION							
	Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Resul t4
Nº of unplanned maintenance interventions		2		2		2		2

	Robot 1	Robot 2	Robot 3	Robot 4
Criticality	22	40	20	20

Criticality Criteria	ASSETS			
	Robot 1	Robot 2	Robot 3	Robot 4
Utilization f.	14.29%	50.00%	40.00%	50.00%
Safety	14.29%	10.00%	10.00%	10.00%
Maintainability	57.14%	20.00%	40.00%	30.00%
O. Reliability	14.29%	20.00%	10.00%	10.00%

Third Hour

Failure Effect		ROBOTS INFORMATION							
		Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Result 4
Operational Impact			4		5		4		5
	Utilization factor	0.58	3	0.87	1	0.68	3	0.97	1
	Quality Impact		3		3		3		3
	Age		4		4		4		4
Safety	*Nº incidents*	0	1	0	1	0	1	0	1
Maintainability	*MTTR*	300	3	232	3	213	3	120	2
Operational Reliability	*MTBF*	312	2	339	2	1374	1	3600	1

Calculations Operational Impact	ROBOTS			
	Robot1	Robot2	Robot3	Robot4
	C	AAA	C	AAA
	C	0	C	0
	C	0	C	0
	C	0	C	0
	C	0	C	0
	C	0	C	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	Result 1 C	Result2 AAA	Result3 C	Result4 AAA

Failure Probability	ROBOTS INFORMATION							
	Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Failures per hour	2	1	2	1	3	2	1	1

Failure Detectability	ROBOTS INFORMATION							
	Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Nº of unplanned maintenance interventions		2		2		2		2

	Robot 1	Robot 2	Robot 3	Robot 4
Criticality	20	22	36	18

Criticality Criteria	**ASSETS**			
	Robot 1	Robot 2	Robot 3	Robot 4
Utilization f.	33.33%	45.45%	44.44%	55.56%
Safety	11.11%	9.09%	11.11%	11.11%
Maintainability	33.33%	27.27%	33.33%	22.22%
O. Reliability	22.22%	18.18%	11.11%	11.11%

Fourth Hour

Failure Effect		**ROBOTS INFORMATION**							
		Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Operational Impact			5		4		3		4
	Utilization factor	0.92	1	0.25	4	0.85	2	0.62	3
	Quality Impact		3		3		3		3
	Age		4		4		4		4
Safety	*Nº incidents*	0	1	0	1	0	1	0	1
Maintainability	*MTTR*	167	2	1342	4	540	4	427	4
Operational Reliability	*MTBF*	826	1	1470	1	2400	1	600	2

	ROBOTS							
Calculations Operational Impact	Robot 1		Robot 2		Robot 3		Robot4	
	AAA		C		B		C	
	0		C		B		C	
	0		C		B		C	
	0		C		B		C	
	0		C		B		C	
	0		C		B		C	
	0		0		B		0	
	0		0		B		0	
	0		0		B		0	
	Result 1	AAA	Result2	C	Result3	B	Result4	C

Failure Probability	**ROBOTS INFORMATION**							
	Data 1	Result 1	Data 2	Result 2	Data 3	Result 3	Data 4	Result 4
Failures per hour	4	2	2	1	1	1	3	2

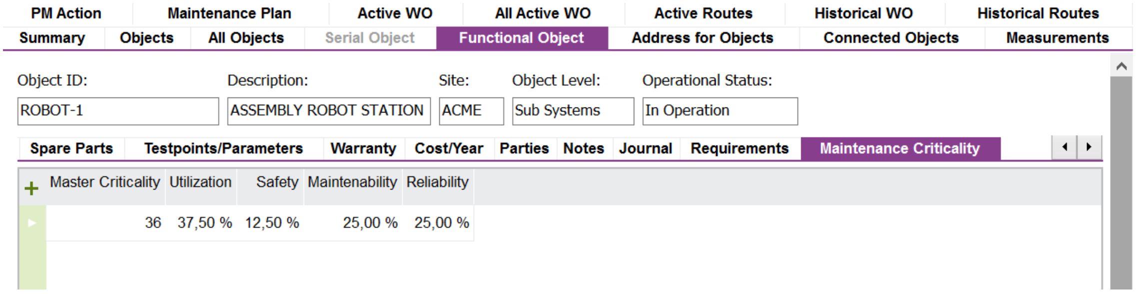
Failure Detectability	**ROBOTS INFORMATION**							
	Data1	Result1	Data2	Result2	Data3	Result3	Data4	Result4
Nº of unplanned maintenance interventions		2		2		2		2

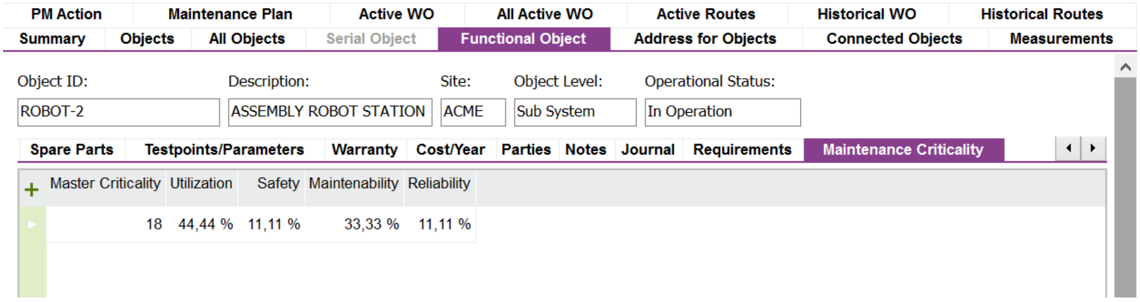
	Robot 1	Robot 2	Robot 3	Robot 4
Criticality	36	20	18	44

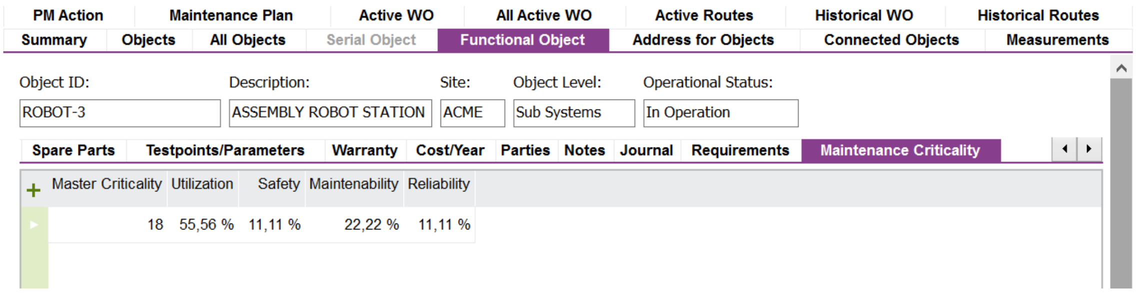
Criticality Criteria	ASSETS			
	Robot 1	Robot 2	Robot 3	Robot 4
Utilization f.	20.00%	40.00%	33.33%	36.36%
Safety	20.00%	10.00%	11.11%	9.09%
Maintainability	40.00%	40.00%	44.44%	36.36%
O. Reliability	20.00%	10.00%	11.11%	18.18%

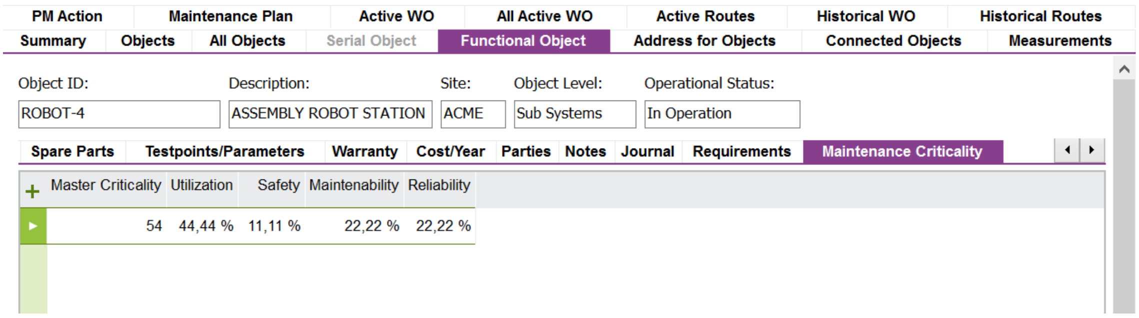
Appendix B: Changing criticality in IFS application

HOUR 1:









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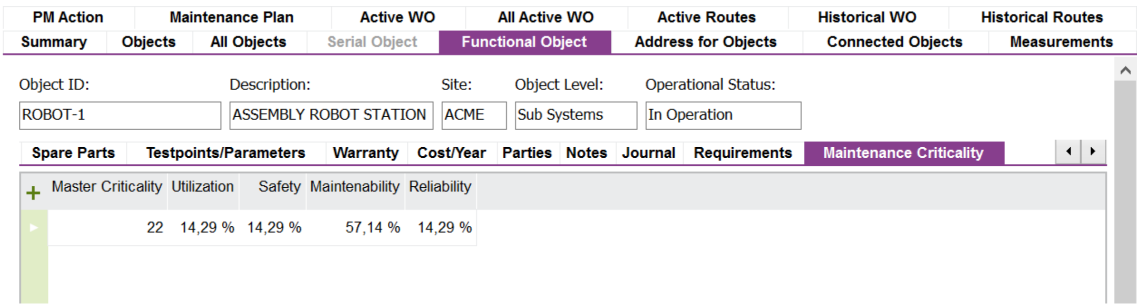

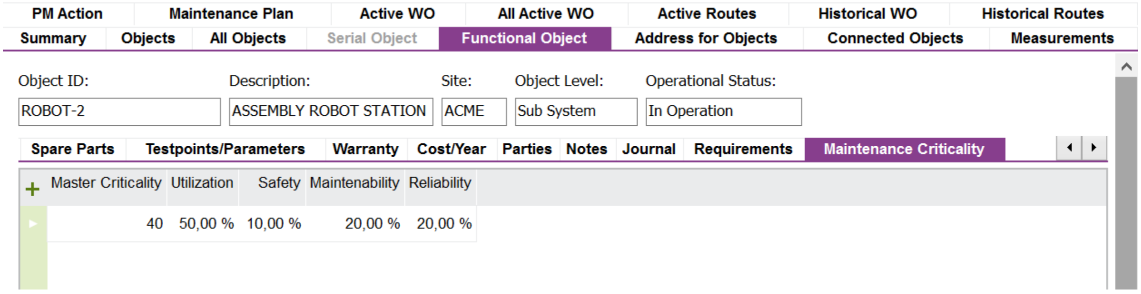
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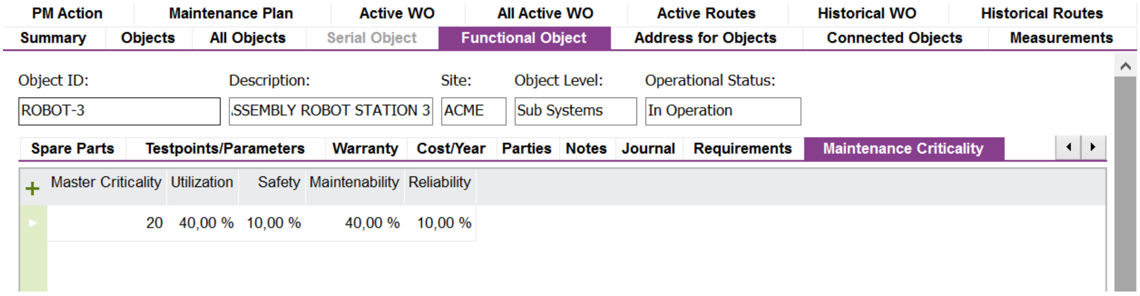
Active Routes
Historical WO
Historical Routes
Summary
Objects
All Objects
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
ROBOT-2
Description:
ASSEMBLY ROBOT STATION
Site:
ACME
Object Level:
Sub System
Operational Status:
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
40
50,00 %
10,00 %
20,00 %
20,00 %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Active Routes
Historical WO
Historical Routes
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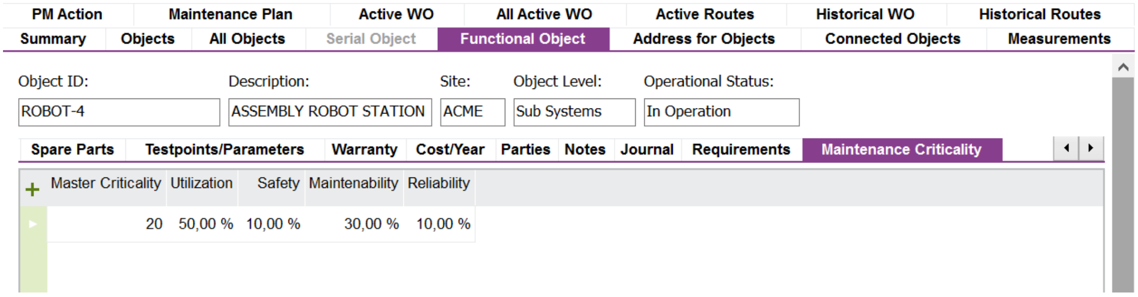
Objects
All Objects
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
ROBOT-3
Description:
SSEMBLY ROBOT STATION 3
Site:
ACME
Object Level:
Sub Systems
Operational Status:
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
20
40,00 %
10,00 %
40,00 %
10,00 %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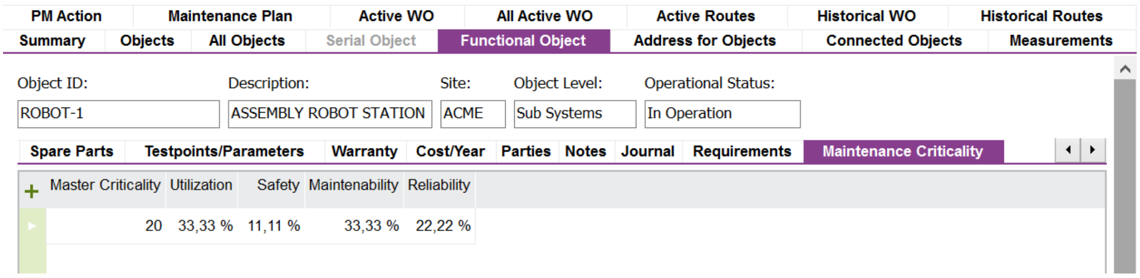
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
ROBOT-4
Description:
ASSEMBLY ROBOT STATION
Site:
ACME
Object Level:
Sub Systems
Operational Status:
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
20
50,00 %
10,00 %
30,00 %
10,00 %

HOUR 3: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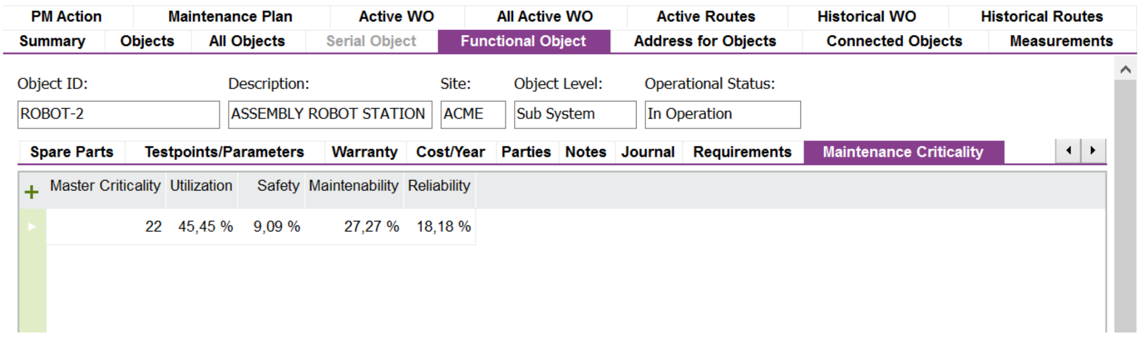
Active Routes
Historical WO
Historical Routes
Summary
Objects
All Objects
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
ROBOT-1
Description:
ASSEMBLY ROBOT STATION
Site:
ACME
Object Level:
Sub Systems
Operational Status:
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
20
33,33 %
11,11 %
33,33 %
22,22 %


PM Action
Maintenance Plan
Active WO
All Active WO
Active Routes
Historical WO
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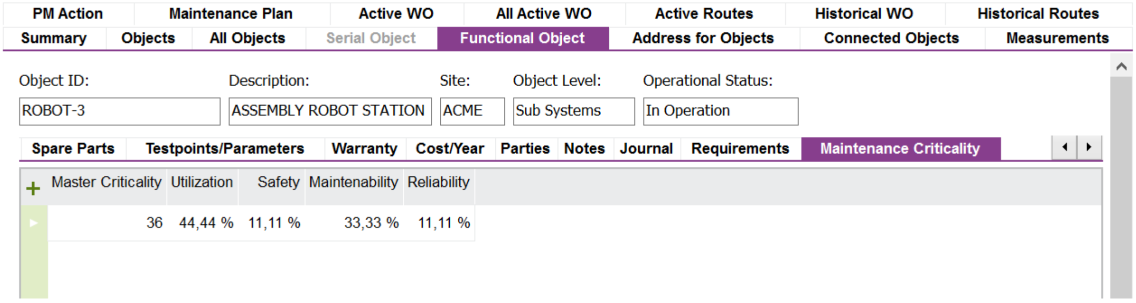
Summary
Objects
All Objects
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
ROBOT-2
Description:
ASSEMBLY ROBOT STATION
Site:
ACME
Object Level:
Sub System
Operational Status:
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
22
45,45 %
9,09 %
27,27 %
18,18 %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All Active WO
Active Routes
Historical WO
Historical Routes
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Objects
All Objects
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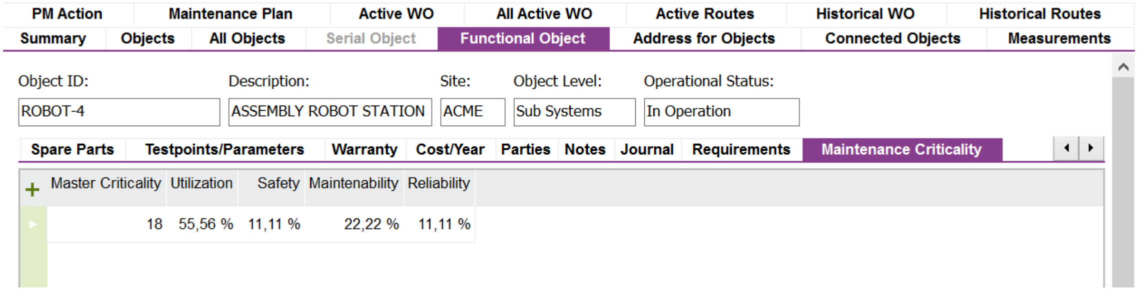
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
Description:
Site:
Object Level:
Operational Status:
ROBOT-3
ASSEMBLY ROBOT STATION
ACME
Sub Systems
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
36
44,44 %
11,11 %
33,33 %
11,11 %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Historical WO
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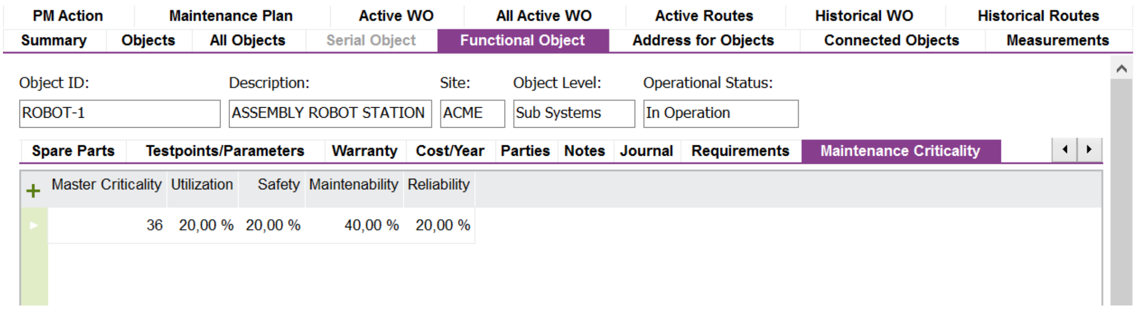
All Objects
Serial Object
Functional Object
Address for Objects
Connected Objects
Measurements
Object ID:
Description:
Site:
Object Level:
Operational Status:
ROBOT-4
ASSEMBLY ROBOT STATION
ACME
Sub Systems
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
18
55,56 %
11,11 %
22,22 %
11,11 %

HOUR 4: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Measurements
Object ID:
Description:
Site:
Object Level:
Operational Status:
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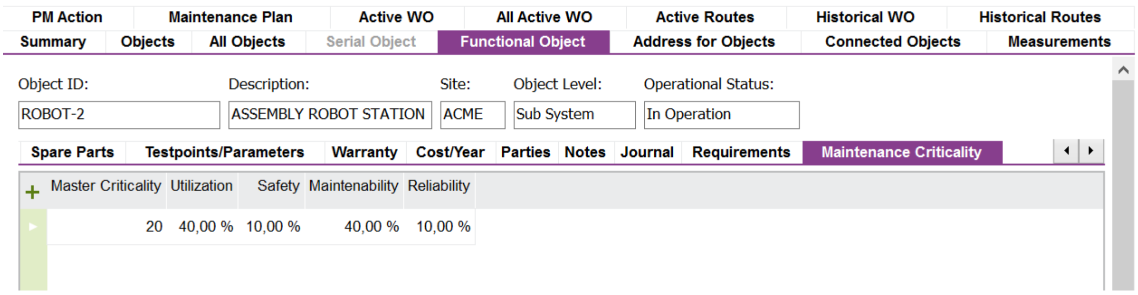
ASSEMBLY ROBOT STATION
ACME
Sub Systems
In Operation
Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
Journal
Requirements
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
36
20,00 %
20,00 %
40,00 %
20,00 %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Active Routes
Historical WO
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Connected Objects
Measurements
Object ID:
Description:
Site:
Object Level:
Operational Status:
ROBOT-2
ASSEMBLY ROBOT STATION
ACME
Sub System
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Testpoints/Parameters
Warranty
Cost/Year
Parties
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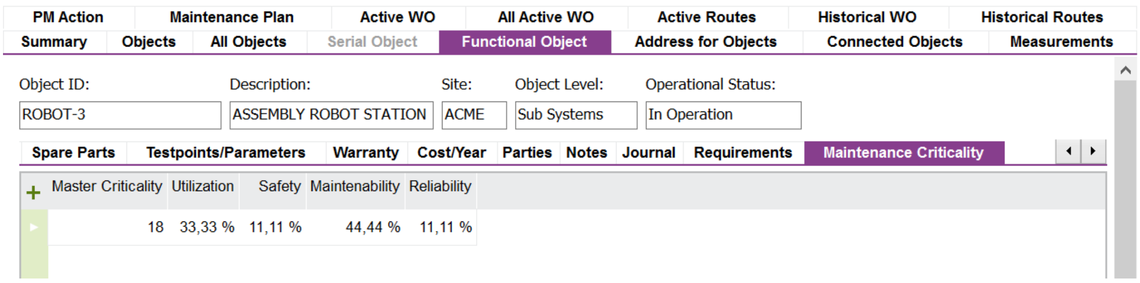
Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
20
40,00 %
10,00 %
40,00 %
10,00 %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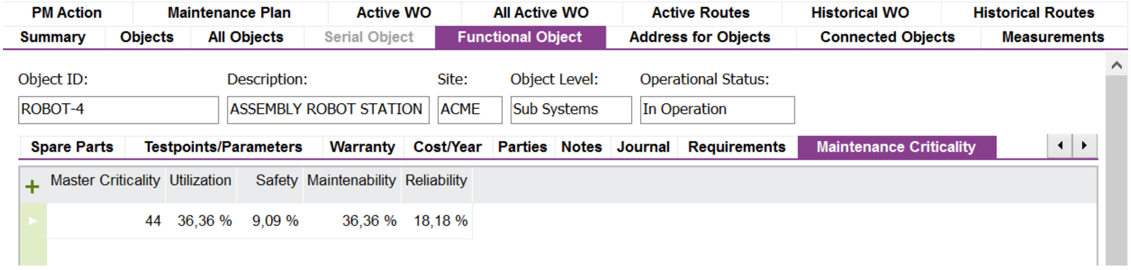
Safety
Maintenability
Reliability
18
33,33 %
11,11 %
44,44 %
11,11 %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Site:
ACME
Object Level:
Sub Systems
Operational Status:
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Spare Parts
Testpoints/Parameters
Warranty
Cost/Year
Parties
Notes
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Maintenance Criticality
Master Criticality
Utilization
Safety
Maintenability
Reliability
44
36,36 %
9,09 %
36,36 %
18,18 %

Appendix C: Data obtained from Axxos servers

Hour 1

MachineName	UtilizationFactor	MTTRinSeconds	MTBFinSeconds	NumberOfFailures
Station 1	0.73	162	518	5
Station 2	0.78	329	1342	2
Station 3	0.90	170	1470	2
Station 4	0.65	139	282	7

Hour 2

MachineName	UtilizationFactor	MTTRinSeconds	MTBFinSeconds	NumberOfFailures
Station 1	0.88	420	3600	1
Station 2	0.88	101	391	4
Station 3	0.75	900	3600	1
Station 4	0.88	208	2400	2

Hour 3

MachineName	UtilizationFactor	MTTRinSeconds	MTBFinSeconds	NumberOfFailures
Station 1	0.58	300	312	2
Station 2	0.87	232	339	2
Station 3	0.68	213	1374	3
Station 4	0.97	120	3600	1

Hour 4

MachineName	UtilizationFactor	MTTRinSeconds	MTBFinSeconds	NumberOfFailures
Station 1	0.92	167	826	4
Station 2	0.25	1342	1470	3
Station 3	0.85	540	1374	3
Station 4	0.62	427	600	3