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Optimization of Manual Headlight Aiming Process at VCC

- An Analysis to Increase Operations Efficiency of a Process in a Production System

Master's thesis in Production Engineering

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Gothenburg, Sweden 2017

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Cover: Manual Headlight Aiming Workstation at Volvo Cars Torslanda plant.

Photographer of Cover Photo: Amra Sedic Team Leader at Volvo Cars Torslanda plant.

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Abstract

Volvo Cars Corporation (VCC) has been continuously strengthening its commitment towards safety, quality and the environment to make life less complicated for people. The company produces a premium range of cars that includes sedans, wagons, sport wagons, cross country cars and SUVs. Headlights being one of the part in the cars delivered to the customers must be aimed correctly for illumination. Incorrectly aimed headlights will create poor visibility for the driver as well as the oncoming traffic and, thereby possibility of occurrence of road traffic accidents. Also in recent years, the headlight aiming precision has increased, this in combination with new designs and different light sources has made it harder for VCC to manually evaluate the headlight aiming. VCC is interested in strengthening its operations efficiency of the manual headlight aiming process.

The purpose of this master thesis was to establish an optimized method as a solution to help VCC carry out the process of headlight aiming. The optimized method suggested will ensure that the cars delivered to the customers are aimed correctly for headlight illumination and, are of high quality and safety. The investigation was carried out through two established scientific methodologies DMAIC and Dynamo++.

The thesis has established an optimized method to improve the operations efficiency of manual headlight aiming process. The recommended solution improves the overall quality achieved by the process and moreover the automation improvement solutions suggested decreases the process time, increases quality and provide insights for VCC to consider towards making the workplace safe and healthier for the operator in the long run.

Keywords: DMAIC, Dynamo++, Quality, Edge Detection, Hierarchical Task Analysis, Automation, Root Cause Analysis, Headlights

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List of Abbreviations

CMOS - Complementary Metal Oxide Semiconductor
DFIP – Design Principle for Information Presentation
DMAIC - Define, Measure, Analyze, Improve, Control
DOE – Design of Experiments
Dynamo++ - Dynamic Levels of Automation for Robust Manufacturing System
ECE - Economic Commission for Europe
ECOS – Electrical Check Out System
EOL -End of Line
FAS – Fahren Assistance System
HID - High Intensity Discharge
HTA - Hierarchical Task Analysis
LED - Light Emitting Diode
LoA - Levels of Automation
LoA Max - Level of Automation Maximum
LoA Min - Level of Automation Minimum
LoA_{cog} - Level of Automation Cognitive
LoA_{phy} - Level of Automation Physical
ME – Manufacturing Engineering
MHA – Manual Headlight Aiming
NASA TLX – NASA Task Load Index
OEM - Original Equipment Manufacturers
PII – Process Inspection and Instruction
R&D – Research and Development
RE ECOS – Re Electrical Check Out System
REBA - Rapid Entire Body Assessment
SAE - Society of Automotive Engineers
SoPI - Square of Possible Improvements
TQM - Total Quality Management
VCC - Volvo Cars Corporation
VCT - Volvo Cars Torslanda
VISP – Visual Inspection System
VSM - Value Stream Mapping
WAE – Wheel Alignment
WCED – World Commission on Environment and Development

1 Introduction

This chapter provides brief background of the Volvo Cars Corporation and, purpose and delimitations for the master thesis. The end of line flow at Volvo Cars Torslanda plant is also explained followed by brief description of the process/station under investigation.

1.1 Background

Volvo Cars Corporation (VCC) produces a premium range of cars that includes sedans, wagons, sport wagons, cross country cars and SUVs. VCC's vision is to be the world's most progressive and desired premium car brand. The company's mission statement is "*Our global success will be driven by making life less complicated for people, while strengthening our commitment to safety, quality and the environment*" **[1]**. The master thesis was initiated by the department of Exterior System and Hatches at Volvo Cars Corporation to improve the quality audit process of headlight aiming.

VCC currently quality audit the headlight aiming of cars using process defined by manufacturing engineering department of 'Exterior System and Hatches'. The process is completely carried out manually and dependent on the operator's judgement using his cognitive skills and what he perceives in his mind as to be the right image of the beam pattern for evaluating the car headlight aiming. Today the best know way of evaluating headlight aiming is to use human eyes looking at a wall according to VCC. VCC has performed several tests to find out how well this manually reading of the headlight aiming full fill their demands and, result is that they are using a lot of the tolerance in this manual process. The headlight aiming precision has increased during last years, this in combination with new designs and different light sources has made it harder for VCC to manually evaluate the headlight aiming. The outcome of manually evaluated headlight aiming process is also used as input to calibrate the automatic headlight aiming equipment installed at three stations in the End of Line (EOL) production system at Volvo Cars Torslanda (VCT) plant. Every car is adjusted for their headlights in one of the three stations using the automated headlight aiming equipment. This makes it a need for improvement of manual headlight aiming process for VCC to improve the quality audit process of headlight aiming of the cars.

1.2 Purpose

The purpose is to establish an optimized method as a solution to help VCC carry out the process of headlight aiming. The goal is to evaluate the existing procedure and look for improvements in the current process or, to find a new process that can provide better results over the current process. The optimized method is investigated by using the following research approaches:

- DMAIC
- DYNAMO++

1.3 Delimitation

The master thesis does not include evaluation of mainline headlight aiming process. Suggestions on automation improvement solution will not include development of cad models.

1.4 Area of Investigation

The following section explains the context behind the product reaching the process and a small description of the station under study in the master thesis.

1.4.1 Context

The EOL production system at the Volvo Cars Torslanda plant explains the flow of the product in reaching the area of interest for the master thesis work. Product in this master thesis refers to cars of different models and variants within models manufactured by VCC. All the stations part of the EOL production system is shown in Figure 1. The complete product flow in reaching the area of investigation at VCT plant is depicted visually in the Figure 2. The premise to the area of interest in the EOL production system goes as follows. The complete assembled product i.e. car is started for the first time and moved to physical check in a moving conveyor line (ECOS). The fitting team physically inspects the car for minor repairs and tests electrical circuitry system. The car is then run over the cobblestone to shake the car to right height. Adjustment of the chassis to the right height in the air suspension station is carried out for cars with air suspension mechanism and cars with mechanical suspension are directly moved to the next station. The next station is the WAE station in the EOL production system. Upon the arrival of the car at the station both wheel alignment and headlight aiming is carried out. The headlight aiming is carried out using an automated equipment according to the specifications defined by the process. Finally, the car passes through the FAS station where cameras and parking sensors are activated and checked. It is followed by picking all the cars manufactured to the markets USA and Canada, and randomly picked cars manufactured i.e. 5 cars of every model in span of 4 weeks for the markets China, Europe and Rest of the World and, moved to a process setup by VCC known as the 'Darkroom Process' for quality check of headlight aiming. The cars are then moved to VISP station followed by RE ECOS.

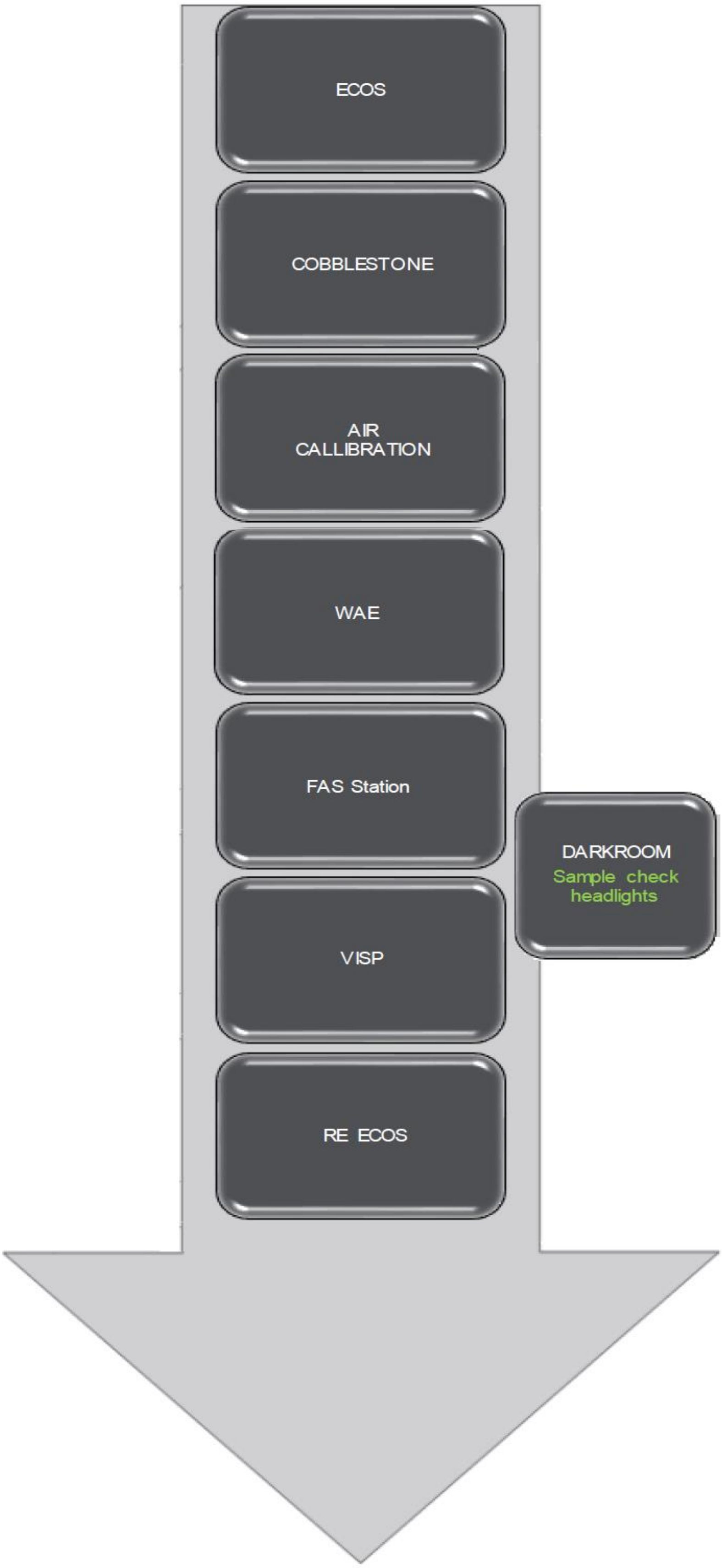

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Figure 1: Stations at VCT's EOL Production System

[1]Image reproduced with permission from Volvo Cars Corporation.

Figure 2: Product flow at VCT's EOL Production System

1.4.2 The Station

Quality check of the headlights (i.e. both measuring the aiming and adjustments) takes place at the 'Darkroom Process[2]', see Figure 3. There are two main reasons to carry out the process at this station. First as quality check to ensure that cars leaving the plant to the customer must be correctly aimed for headlight illumination. Second is to use the results as input for calibrating the automated headlight aiming equipment in the EOL production system i.e. if the headlights are out of specification limits, the operator from darkroom process workstation informs the operator at WAE station to calibrate the automated headlight aiming equipment. Currently the process at darkroom is carried out by performing manual tasks with the trained operator judging the aimed headlights from the EOL station to measure and document values, and if required adjust to ensure quality of the product. The process has resulted in unreliable results, which is matter of concern for VCC. VCC believe it is difficult for the operator to ensure quality check in the current state and need improvement in the process. Hence the authors will focus on providing insights into improving the process towards obtaining reliable results or find a new method to replace the existing process.


[3]

Figure 3: Darkroom Process Work Station at VCT

[2]'Darkroom Process' is referred to as 'Manual Headlight Aiming Process' by the authors in the report.
[3]Image reproduced with permission from Volvo Cars Corporation.

2 Theory

The following chapter contains the established literature referred by the authors in the master thesis. In general, the concepts related to production systems, in particularly manufacturing engineering field are explained.

2.1 Production Systems

In today's industries systems thinking is more emphasized, this development could be owed to the transition of manufacturing industries in the 90's where the era of systems perspective/holistic perspective arrived leaving behind the era distinctive with machines **[2]**. This is totally in line with the thoughts of authors Bellgran and Säfsten where they present a systems perspective as a helping aid in clearly understanding the components of production systems and their interaction towards developing and operating new production systems **[3]**.

Production system is often referred to as transformation system converting input (could be raw material) to output (could be product) with the intermediary transformation phase constituting processes together with human and technical system aiding in realizing the product/ desired output **[3].** Other important factor to consider is that output from a system could be input to another system.

The systems are classified into three perspectives **[Ibid.]**:

- Functional perspective - where the system is considered as transformation unit converting input to output.
- Structural perspective - where the system constitutes different elements and relation between them.
- Hierarchical perspective - where system implies that one system can be a sub system of bigger system.

2.2 Process

A process is an activity that constitutes series of tasks to be carried out, by defined input to obtain defined output. Related to production system Ljungberg and Larsson defined process as "*repetitive network within a certain order of linked activities using information and resources to transform 'object in' to 'object out', from identification to satisfaction of customer needs*" **[3]**. In simple terms, a process is defined as "*network of activities that are repeated in time, whose objective is to create value to external and internal customers*" **[4]**.

In a manufacturing system within a company several processes exist and can be divided into two types according to Harrington **[3]**.

- Production Process: Referring the term to a manufacturing company, the activities in production process are to develop and produce products i.e. activities associated in realization of product being distributed to the end customer. A production process also referred to as a main process can be divided into sub process and activities.

- Business Process: A series of processes that supports the production process. It is further divided as support process and management process. While the former is established in a manufacturing company to keep the main business working, the later facilitates the coordination of support process and production process. The overview of process according to Harrington, see Figure 4 **[Ibid.].**

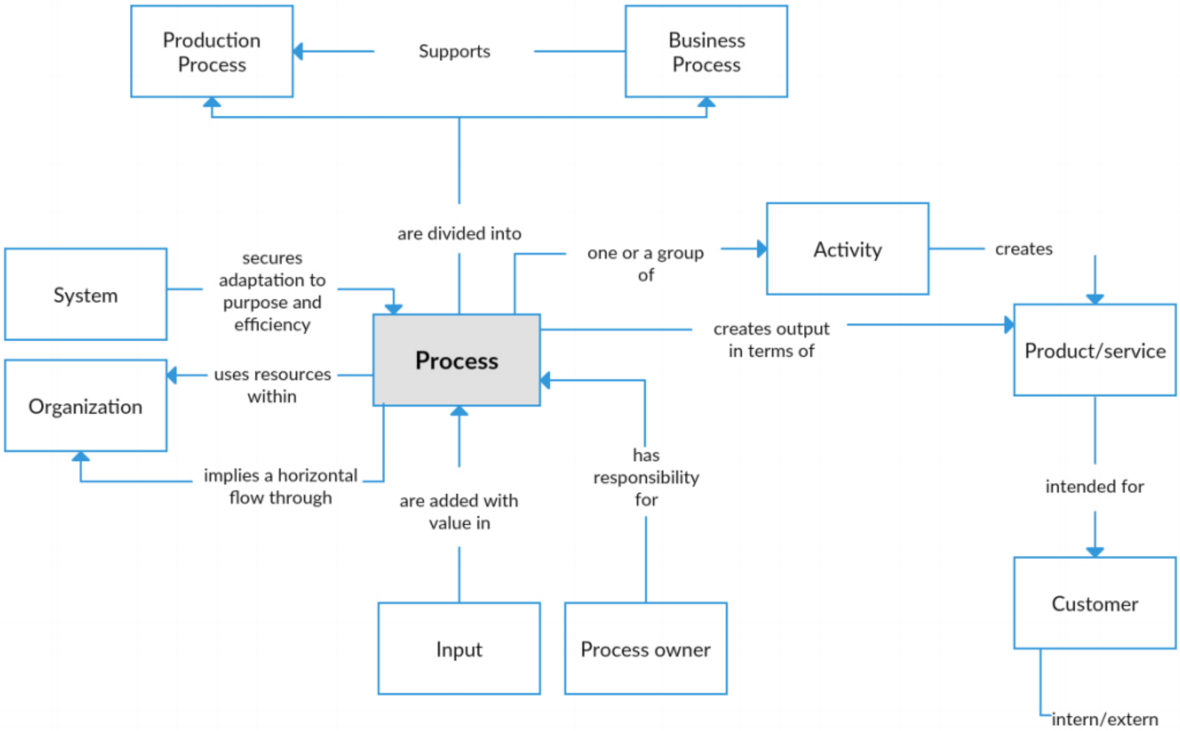


Figure 4: Process Overview, adapted from Harrington [3]

2.3 Continuous Improvement

Continuous improvement also referred to as continual improvement is synonymous to in progress improvement of products/services/processes **[5]**. It is achieved through two approaches i.e. either through incremental (improvement over time) or breakthrough (improvement at once). Often continuous improvement is executed through various methodologies like DMAIC, PDCA, Lean and Total Quality Management (TQM) **[Ibid.]**. This approach is often taken by enterprises towards staying competitive in the market **[6]**. Also, significant to note is the fact of different motivations for the different business enterprises to take the approach of continuous improvement, but the grinding thought for every new millennium business enterprises and their leaders has been "*How do we stay successful?"*. This is where many companies look up towards Toyota and General Electric (GE) as they are constantly setting new standards and remain leaders in aspects of continuous improvement. Aartsengel and Kurtoğlu makes an interesting revelation here saying that other companies just try to replicate the principles thinking that they can reach that position and stay competitive without realizing the fact that the results at Toyota and GE have been achievable due to patterns of continuous improvement through experimentation rather than just following practices and techniques documented in literature. Aartsengel and Kurtoğlu also presents a solution by clearly justifying the real need for enterprises to look upon continuous improvement as a business investment that adds value in long term and emphasizes enterprises to take up initiatives of continuous improvement towards increasing profits in short term and sustain them in the longer term **[Ibid.].**

Quality management clearly defines the need for quality tools and methodologies in realizing the principles of quality, see Figure 5 **[4].** The interdependencies can generally be implied as follows where initially the need to select a methodology that supports a principle followed by a tool to visualize the same **[Ibid.]**.

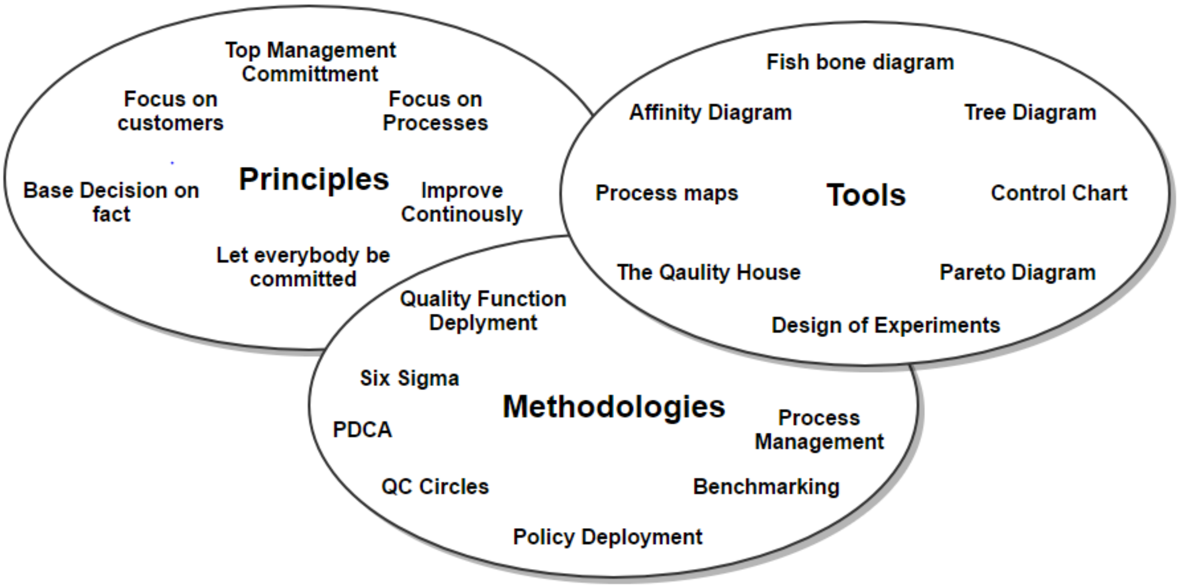


Figure 5: Quality Management, adapted from Hellsten et al. [4]

Quality

"*The Quality of a product (article/service) is its ability to satisfy or preferably exceed the needs and expectations of the customers*" **[3]**. Quality in the aspect of process could be defined controlling the process towards ensuring predictable and reliable outcomes, which is totally in line with Deming's perspective of quality aiming towards achieving stable process **[7]**. As costs of poor quality often constitutes 30% of sales, it is of high importance to eliminate them towards increasing profits for an organisation **[4].**

2.4 Automation Strategies

"*Automation is a technology by which a process procedure is accomplished without human assistance*" **[8]**. The need for Automation at manufacturing companies in their production system has increased over the years due to several challenges that includes increasing productivity, better efficiency, high flexibility, higher quality, ergonomic improvements and more **[9]**. It is suggested that a comprehensive study must be conducted to integrate appropriate technology for the manufacturing systems **[8]**.

Hence a need for scientific methodology was first indicated by Groover and Jayaprakash **[ibid.]**.

The levels of automation as defined by Frohm is *"The allocation of physical and cognitive tasks between humans and technology described as continuum ranging from totally manual to totally automatic"* **[9]**. The scales presented by Frohm, see Figure 6.

LOA	Physical	Cognitive
1	**Totally manual** – Totally manual work, no tools are used, only the users own muscle power E.g. The users own muscle power	**Totally manual** – The user creates his/her own understanding for the situation and develops his/her course of action based on his/her earlier experience and knowledge E.g. The users earlier experience and knowledge
2	**Static hand tool** – Manual work with support of static tool E.g. Screwdriver	**Decision making** – The user gets information on what to do or proposal on how the task can be achieved E.g. Work order
3	**Flexible hand tool** – Manual work with support of flexible tool E.g. Adjustable spanner	**Teaching** – The user gets instruction on how the task can be achieved E.g. Checklists, manuals
4	**Automated hand tool** – Manual work with support of automated tool E.g. Hydraulic bolt driver	**Questioning** – The technology question the execution if the execution deviate from what the technology consider being suitable E.g. Verification before action
5	**Static machine/workstation** – Automatic work by machine that is designed for a specific task E.g. Lathe	**Supervision** – The technology calls for the users attention and direct it to the present task E.g. Alarms
6	**Flexible machine/workstation** – Automatic work by machine that can be configured for different tasks E.g. CNC-machine	**Intervene** – The technology takes over and corrects the action, if the execution deviate from what the technology consider being suitable E.g. Thermostat
7	**Totally automatic** – Totally automatic work, the machine solve all deviations or problems that occur by itself E.g. Autonomous systems	**Totally automatic** – All information and control is handled by the technology. The user is never involved E.g. Autonomous systems

Figure 6: Physical and Cognitive Scales, adapted from Frohm [10]

These scales were adopted by Fasth to create a more refined version of the definition and develop level of automation evaluation matrix. The definition goes as follows *"The allocation of physical and cognitive tasks between resources (humans and technology), described as discrete steps from 1 (totally manual) to 7 (totally automatic), forming a 7 by 7 LoA matrix containing 49 possible types of solutions"* **[10]**.

The evaluation matrix also suggests the general areas in which processes under different manufacturing automation i.e. automated system, semi-automated system or manual at different stages in production systems at a manufacturing company might integrate **[11]**. For example, in general the final assembly stations at manufacturing company's production system must usually be integrated between levels shown in the LoA matrix, see Figure 7. Human and technology integrations must regard noteworthy attention to design and redesign process in production systems at manufacturing companies **[Ibid.]**.

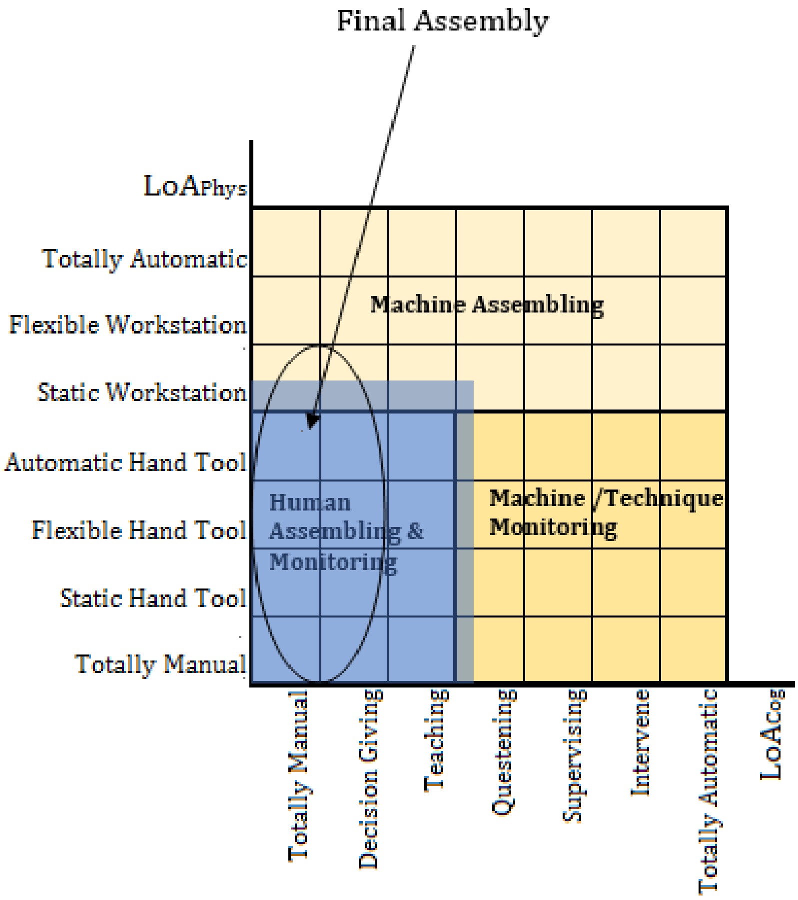


Figure 7: LoA Matrix, adapted from Dencker et al. [11]

2.5 Ergonomics

The origins of ergonomics discipline which dates to the times of World War II, is more synonymous with building workplaces adaptable to diverse group of workforces **[12]**. Ergonomics generally includes majority of the work aspects involving human activity.

Production ergonomics aims at designing safe workplaces, one that is free from risks of injuries, pain, discomfort and confusion. The two parts cognitive and physical aspects are demanded by production ergonomics to design process or production system. Achieving better performance of the production system with human as integral part of it is quintessential to keep up the productivity and competitiveness **[Ibid.]**.

Physical Ergonomics

Muscles, the joints and skeleton forms the structure of human body for movement, to withstand physical loads to work and get back the body to normal state from fatigue and pain **[12]**. If the tolerance limit of the musculo-skeletal loading is exceeded at a point that a worker can bear, it will disable the worker to handle physical loading and leads to 'Work-related Musculo-Skeletal Disorder'.

Surpassing the physical ability to withstand biomechanical loading results in pain and physical injury, that is either sudden or chronic. From engineering perspective, physical loading is termed as risk when posture, time and force combine resulting in pain and physical injury. Berlin and Adams adopt this view, see Equation 1.

Physical Loading = posture * forces * time ……………………… Equation 1

Posture refers to the ability of the human body to work and maintain a position that constitutes internal loading. It refers to the distribution of internal forces across different parts of the body while executing a task. Forces refers to external loading because of handling weights in various form through pushing, pulling and other activities that contributes for the same. Time is influenced in numbers by the longevity and repetitiveness of physical loading during the execution of task **[Ibid.]**.

Cognitive Ergonomics

Cognitive ergonomics refers to the sensory signals received by brain for a worker to understand and execute the task **[12]**. The focus of addressing cognitive ergonomics aspect at workplace design is to portray right information and create better physical cognitive support for the operator to understand the status of the task, interpret the information and enact rightly during the execution of the task. Designing workplaces by addressing the issue will reduce the frequency of occurrence of danger, mental overload, confusion, irritation and errors in the process. Effort and time frame of finding the information must be lesser and shorter respectively for the operator. The higher the effort and longer the time needed for the operator to perform task, leads to less motivation for the operator and ultimately achieving reduced efficiency in the process.

The typical approaches to address cognitive ergonomics is through development of work instructions and standardized work. Work instruction helps the operator in finding relevant information for executing the tasks in the process. Standardized work enables an advanced practice to be developed to execute the task irrespective of the operator performing the process in a shift at the production plant **[Ibid.]**.

3 Methodology

This chapter depicts the methods and tools used in the master thesis. It is organised by describing short theory behind established methodologies and required tools for realizing it. Moreover, common methods adopted for both the methodologies, ethical considerations and research quality are also presented in this chapter.

3.1 DMAIC

Continuous process improvement forms the premise for any organization to stay competitive in the market **[13]**. DMAIC is one such continuous improvement methodology, which employs a bunch of tools and techniques in a reasonable way to reach at solutions. It enables the organizations to reach and maintain a competitive position related to product and process in the competitive world. DMAIC in the context of a process is executed collaboratively and can be visualized, see Figure 8 **[Ibid.]**.

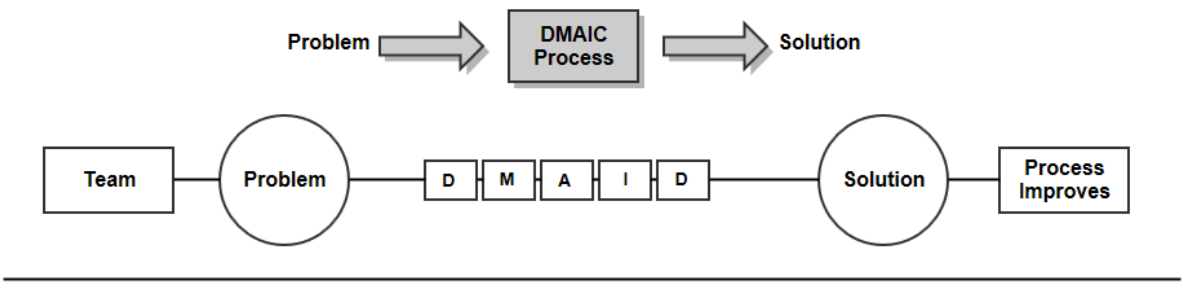


Figure 8: DMAIC for Process Improvement, adapted from Shankar [13]

The methodology was modified and applied in accordance to the master thesis requirements. The specific tools used in each of the individual phases of DMAIC, see Figure 9.

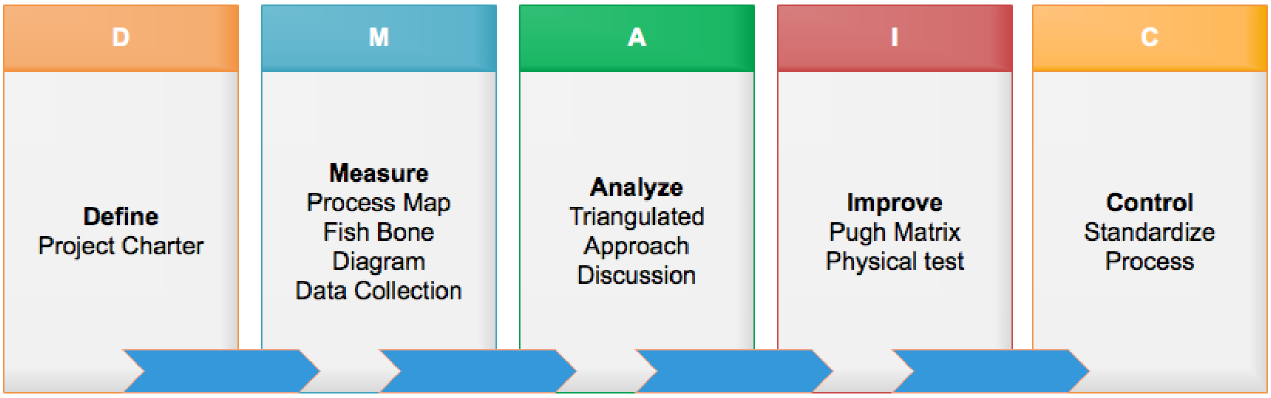


Figure 9: Tools Adopted in DMAIC Phases

The intermediate transformation phase forms the core of process improvement and constitutes the different phases of the methodology, presented below:

3.1.1 Define

The define phase makes sure the management support and linkage of problem to the organization's priorities **[13]**. This phase is generally initiated by walking around determining the problem along with laying out objectives, deliverables and completes with clearly defining the scope of the project. A project charter tool was used, that presents overview of the project along with timeline for the project. In the define phase during DMAIC projects it is used to plan the phases and is referred and updated throughout the life of the project **[Ibid.]**.

3.1.2 Measure

The measure phase ensures better understanding on the current state of the problem, by gathering comprehensive information about the problem **[13]**. This phase is generally initiated through data collection towards quantification of the problem in the current state, which is essential to compare and quantify the improvement in the later phase **[Ibid.]**. The measure phase was carried out by first developing a process map that led to identifying the root causes for the process through a fishbone diagram. Narrowing down the root cause led to the planning and executing a data collection to document the variation in current process. Each of the activities carried out in the phase can be seen in the Figure 10 and explained below.

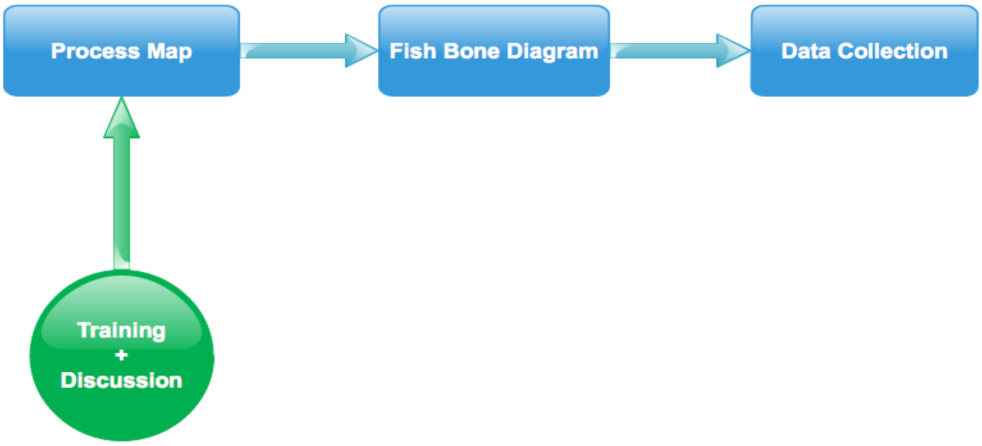


Figure 10: Activities Carried in Measure Phase

Process Map

Process maps are generally created to develop a better understanding of the process **[13]**. Based on the level of detail there are various types of process maps like SIPOC diagram, value stream mapping (VSM), Flowchart. Process map in the form of Flowchart is a tool often used to design a procedure, and contains detailed information about the process including the stages in the process **[Ibid.]**. The process map of the manual headlight aiming process typically represents a top-down flow chart; it was developed based on the observations at plant and performing the task on being trained as operator for two shifts. The inputs from process instruction and inspection (PII) and a discussion with the developer of PII served as guiding factor to understand the detailing tasks carried out during manual headlight aiming process.

Fish Bone Diagram
Fish bone diagram also referred to as cause and effect diagram is a tool that enables one to identify all the possible causes for an effect/problem **[14]**. It's often employed in brainstorming sessions towards identifying probable causes affecting the outcome. It also helps in categorizing the causes **[Ibid.]**. The fish bone diagram was developed based on process map, observation & training at the plant. Developing a fish bone diagram helped the authors to identify the main causes along with primary and secondary causes affecting the process outcome. This helped in narrowing down the main cause for further analysis**.**

Data Collection
The following scenario formed the premise to carry out the data collection procedure. Initially a fishbone diagram was developed to understand the probable causes affecting the process outcome. Data collection was planned for further analysis of the identified main cause affecting the process. The main mode adopted to collect the data was through observation: a controlled study through which the authors aimed to understand the cause-and-effect relationships **[12]**.

3.1.3 Analyze

The analyze phase aids in arriving at better comprehension in terms of cause and effect relationships in the process **[13].** This phase is initiated by analysing the data from the measure phase, followed by further data collection of process after pilot changes and then finally analysis of data got after changes. This leads to finding insights to various improvement solution for the process **[Ibid.]**. The authors used a triangulated approach as tool towards finding the possible improvements to the current process or find an alternate solution to the current process.

Triangulated Approach
A triangulated approach that includes literature, qualitative and quantitative study was initially planned to be used as a tool as a part of the analyze phase of the DMAIC approach to find solutions to improve the process **[15]**. As the master thesis progressed a quantitative study was deemed unnecessary as the authors felt that the usefulness of such a study for this master thesis will not add value. Hence only literature study and qualitative study was conducted. A preliminary qualitative study was conducted in form of interviews with different expertise at VCC with the main aim of collecting valuable inputs in the form of qualitative data for the master thesis and to help the authors to initiate an extensive literature study. R&D Engineer, Tooling Engineer and Active Safety Engineer with expertise connected to headlights and darkroom process at VCC were interviewed to get a broader perspective on the problems, needs and requirements for betterment of the process. It was followed by literature review to search similar studies to find established work in the field of headlight aiming of an automobile. The theoretical data collection through the literature study was initiated using two criteria within technologies and methodologies linked to headlight aiming process of an automobile. The first criteria being able to find solution for the identified main cause and the second criteria being able to find new methods for carrying out headlight aiminig

process in automobile original equipment manufacturing companies. The literature was collected from Google Search, Chalmers Library and the electronic databases supported by Chalmers University of Technology that included Scopus, Access Engineering, IEEE Xplore, ProQuest and Sciencedirect.

Discussion

A focussed group discussion session was initiated to validate the research findings. Key personnel were identified through stakeholder analysis at VCC to present the research findings. The key identified stakeholders included for discussion session were selected based on the need to cover both technical as well as methodological expertise. Therefore, the personnel present during the discussion were the R&D engineers, tooling department engineers from the VCT plant and primary stakeholders from manufacturing engineering department associated with the process.

3.1.4 Improve

This phase aids in realizing the actual improvement based on the input from the previous phases **[13]**. Possible tool that could be employed in this phase is design of experiments (DOE), Pugh matrix and physical implementation. This phase generally enables modelling the new process based on inputs and outputs together with providing possibilities for better understanding of significant input factors and controlling them. It also opens window for continuous improvement in future **[Ibid.]**. The authors have used a Pugh Matrix and carried out a physical test of the chosen solution.

Pugh Matrix

The Pugh matrix generally referred to as the decision matrix owes its name to the inventor Stuart Pugh **[16]**. This matrix facilitates the evaluation of solution alternatives against a certain list of important criteria's. The main aim of this matrix is to identify the most appropriate solution option that best meets the expectations of the criteria's. Pugh matrix just intends to simply serve as a platform for judgemental evaluation of multiple solution options against criteria's and does not mean to be a mathematical matrix. Relating to the sample Pugh matrix visualization in the Figure 11, criterions are represented on the vertical axis whereas horizontal axis represents alternative concepts evaluated based on the concept selection legend. The same Pugh matrix was used in the improve phase of the DMAIC approach **[Ibid.]**. Criteria's were selected by authors upon overviewing the VCC's internally developed Pugh matrix and authors own conscience as per the requirement to evaluate the alternative solution in the master thesis. Importance rating was selected by forming an opinion by the authors upon the 2 key stakeholders identified in the analysis phase. The two key stakeholders were ME and R&D experts related to headlight and darkroom process at VCC. The scales can be selected by researchers depending on their choice for the study. Hence the authors assigned a scale of 5 for each criterion and input the values for ME and R&D experts. This was summed up to obtain a final value for the importance rating on a scale of 10 to input in Pugh matrix.

Pugh Matrix

Concept Selection Legend

Better	+
Same	S
Worse	-

Key Criteria	*Importance Rating*	Benchmark Option	Alterantive 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
			Solution Alternatives				
Criteria 1							
Criteria 2							
Criteria 3							
Criteria 4							
Criteria 5							
Sum of Positives							
Sum of Negatives							
Sum of Sames							
Weighted Sum of Positives							
Weighted Sum of Negatives							
TOTALS							

Figure 11: Pugh Matrix, adapted from Lønmo and Muller [16]

Physical Test

The solution suggested as part of the master thesis was physically tested by the authors as the requested resources were provided by the primary stakeholder at VCC. It should be implemented and further tested by running a batch of trial at the production by VCC if it seems legitimate for the process towards improvement.

3.1.5 Control

This is essentially the last phase of DMAIC process improvement methodology. On realization of the improvement and having a good understanding of significant inputs and impacts of them on the output, the control phase kicks in to ensure control over all those significant input factors **[13]**. The phase puts forward suggested action plan for monitoring the implemented solution in the future. Measurement system analysis and standardization of the process are the two commonly used tools in this phase **[Ibid.]**. For the master thesis standardize process was initially adopted as a tool. The authors did not carry out this step due to set delimitations.

Standardize Process

This tool outlays suggestions in the form of creating work instructions to carry out the process using the new suggested solution **[13]**. New work instructions must be developed and integrated into the PII's at VCC to help the operator carry out the process.

3.2 Dynamo++

Dynamo++ was developed in '2004 - 2007 DYNAMO project' in association with five companies **[17]**. A sixth company was used to validate the methodology. The methodology has four phases and under each phase it has three steps to be carried out. This methodology enables the companies to select the right level of automation for their manufacturing processes or production system. Firstly, the chosen manufacturing process or production system in the pre-study phase of the method will map the flow of product and information, followed by measuring and documenting the current state level of automation for the manufacturing processes or production system under study. The next phase advances the study to consider future possibilities of increasing the level of automation for the manufacturing process or production system. The last phase being the implementation enables the company to plan and execute necessary changes to increase the level of automation physically for the manufacturing process or production system and, follow it up to review that desired result is achieved **[Ibid.]**. Generally, the steps in different phases of the Dynamo++ methodology are repeated until the desired results are achieved and is often combined with different scientific tools to ensure that the manufacturing process or production system is not subjected to over-automation or sub-optimization because of the study **[10]**. The overview of Dynamo++ and tools adopted for the master master thesis, see Figure 12.

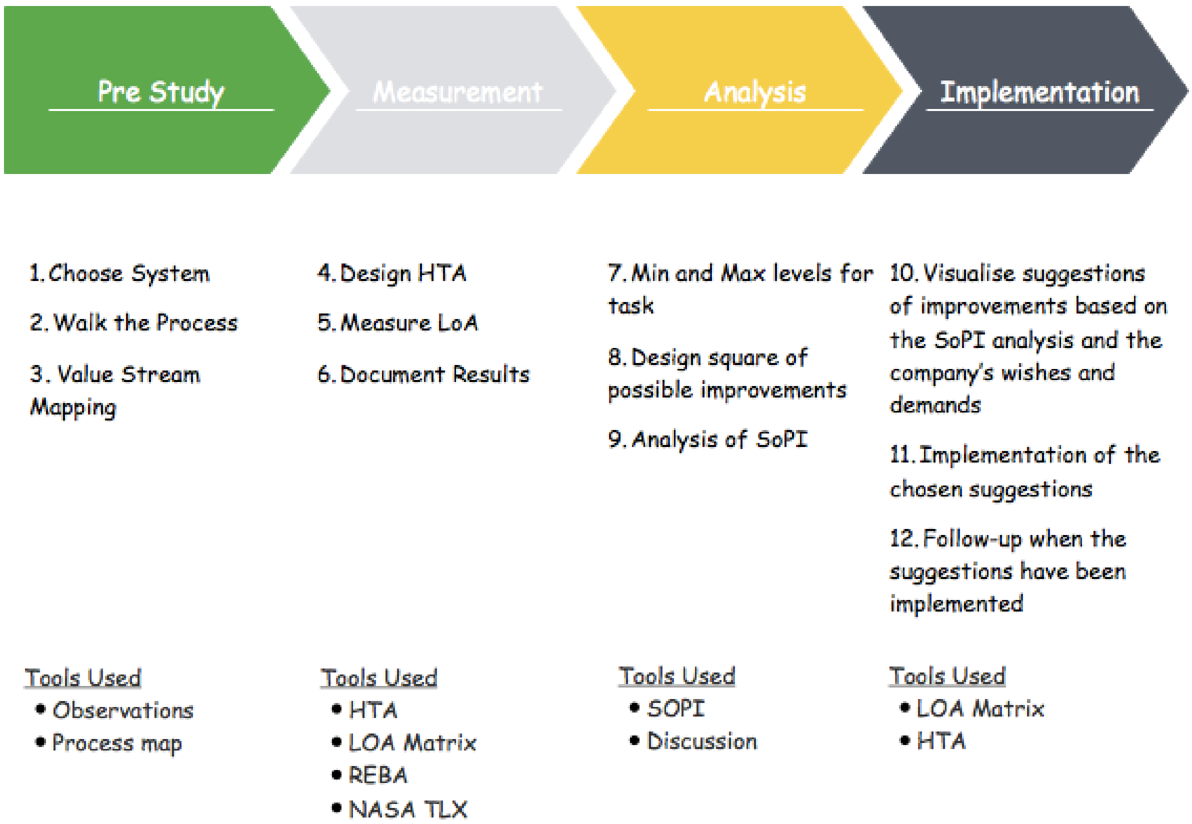


Figure 12: Adopted Dynamo++ Methodology

3.2.1 Pre-Study

1) Choose System - Manufacturing Process/Production System for the study is selected depending on stakeholder's requirement **[17]**. The chosen station for the study with stakeholder agreement is presented in the results chapter.
2) Walk the Process - Various parameters are then identified that might typically include number of work station, numbers of operators, equipment's, bottlenecks etc. through observation **[17]**. The parameters identified by the authors for the master thesis includes number of operators, shifts, tool's used, number of tasks and ergonomic risk postures, bottleneck and process time for the product.
3) Value Stream Mapping (VSM) - A VSM will help to map the flow of the product and information **[17]**. A VSM was not developed as the authors did not see the requirement for it during master thesis. Instead a process map as explained in DMAIC, see section 3.1.2 was developed to depict the flow of activities in the process.

3.2.2 Measurement

4) Design Hierarchical Task Analysis (HTA) - A HTA is then developed by identifying the main tasks and subtasks and, further sub dividing the operations carried by operator depending on the level of detail required **[17]**. The same approach was used by the authors. HTA is a generally used methodology for task analysis. In this method process is divided hierarchically into main tasks, subtasks and operations under sub tasks **[18]**. According to Shepherd HTA provides a very clear understanding on the actuals of the tasks and the conditions in which they are performed, therefore opening window for improvements, irrespective of the individual be it the process owner from management, supervisor, operator etc. HTA basically gives overview of the whole tasks and the order in which they are executed. The development of HTA could either be done by observation or by manually taking step by step input from the performer of the task. The degree of detailing of HTA mainly depends on the purpose. Also, task analysis in the form of HTA helps understanding the human requirements in the tasks of the process and designing the process tasks consistent to the performer of the process **[Ibid.]**.
5) Measure Level of Automation (LoA) - All the tasks identified for the process are then assigned a value from the range of one to seven in both physical and cognitive level **[17]**. The assigned values are then input to the LOA matrix **[Ibid.]**. All the tasks identified for manual headlight aiming process were assigned a value from the range of one to seven in both physical and cognitive level and were then input to the LOA matrix by the authors. An additional tool used in this step included ergonomic evaluation method. Ergonomic analysis for the identified task that poses a risk was performed using the ergonomic evaluation methods explained below.
Ergonomic Evaluation Methods
The selection of ergonomic evaluation method depends on the tasks the operator performs to complete the process **[12]**. There are several methods established that falls under three categories i.e. posture based analysis, biomechanics-based analysis and analysis based on combination of environmental factors **[Ibid.]**. The methods adopted

and used in master thesis are explained below.

Rapid Entire Body Assessment
Synonymous to the full form of acronym REBA, it's a method for evaluating body postures taken in work tasks with focus on the entire body **[19]**. The assessed postures obtain a score in a range of one to fifteen which, indicates the need for necessary actions to be taken for the future **[Ibid.]**.
NASA TLX
It's a methodology to measure the total physical and mental workload, which is based on a questionnaire where the individuals can rate their workplace or task based on six different criteria of physical and cognitive loading and, support **[20]**.
6) Document Results - The level of automation in the current state obtained through the completion of the previous steps are documented **[17]**. The authors documented the same during the master thesis.

3.2.3 Analysis

7) Min and Max levels for task - A workshop is conducted that generally includes process owners and other stakeholders involved within the study like operators, production planner etc. to decide the maximum and minimum level for different tasks in the system based on the triggers for change **[17]**. Due to time limitation, a discussion session was held instead of workshop by the authors. The people included were manufacturing engineers associated with the process and thesis supervisor from Chalmers University of Technology to decide the maximum and minimum level for different tasks in the system based on the triggers for change i.e. quality and ergonomic.
8) Design square of possible improvements (SoPI) - An SoPI is developed based on the minimum and maximum level chosen for each task **[17]**. The authors developed SoPI's that is presented in the results section.
9) Analysis of SoPI - Analyse SoPI for task or operation optimisation due to triggers of change **[17]**. A task optimisation SoPI was developed to further analyse the improvement thoughts for tasks by the authors.

3.2.4 Implementation

10) Visualise suggestions of improvements – Results to stakeholders must be presented based on the SoPI analysis and, the company's wishes and demands **[17]**. A new HTA and LoA matrix was developed by authors to convey results for the stakeholder's.
11) Implementation of the chosen suggestions - Carry out the improvements in the manufacturing process/production system **[17]**. Authors did not carry out the improvements in the manufacturing process due to delimitations.
12) Follow-up when the suggestions have been implemented - To observe the effect of improvements implemented based on the triggers of change **[17]**. Authors did not carry out the step due to delimitations.

3.3 Data Collection

Data generally can be collected in two ways that involve personnel i.e. through quantitative or qualitative research **[12]**. Quantitative research focuses on measuring and quantifying numerical data while on the other hand qualitative research emphasizes on inputs based on experience that helps the researcher to understand the process, reasons and interdependencies to the project goal. In a quantitative study, it is important to ensure the preciseness about the study under measurement to avoid ambiguities during the interpretation of the result. A qualitative data collection involves interaction with people for e.g. interviewing, observation and discussion. This type data is used during various phases in a project. While using this type of data at the beginning of a project enables the project group to understand the basic concepts of the project goal, during later stage of the project this type of data helps to validate the newly recognized findings during the project. The detailed and in-depth answers obtained, through small sample sizes/fewer people entitles or qualify the richness in the study **[Ibid.]**. An important aspect to ensure in data collection is that people involved are persuaded and honest in the study, which can be achieved by conveying the purpose of investigation, and guaranteeing anonymity to the interviewee **[21]**.

Observation

This is generally regarded as the most prevalent method for data collection **[21].** It is carried out at random intervals depending on the requirement in the study, but is also rather executed in a more controlled manner when the purpose needs to serve a scientific setting. The degree of structure is quintessential for data collection. Typically, a high structure employs a checklist for certain occurrences, whereas a low structure refers to listing everything that occurs **[Ibid]**. Observational studies help the researcher to understand the cause-and-effect relationships, without manipulating any of the events in the planned study **[12]**.

Interview

This is generally carried out based on series of oral questions with due importance towards both degree of structure and standardization **[21]**. Structure refers to the extent of openness in interviewee's answers, whereas standardization relates to the interviewer's freedom to remodel questions and form new questions as a follow-up voluntarily **[Ibid]**.

Discussion (Focus Group)

Discussion are one more form of alternatives to interview and are conducted when time limitations object the researchers to include all the stakeholders to collect data required for the research work in a quick way.

3.4 Ethics

During a research study, the authors should generally address ethical considerations related to four ethical principles which are *privacy invasion, informed consent, harming participants* and *deception* according to Bryman and Bell **[22].** The first principle invasion of privacy concerns the acceptance level of liberalism by the humans. This usually arises during photographing and filming videos for the research study. No videos of the humans were taken during the master thesis. However, during ergonomic analysis the operator performing the process needed to be photographed for various positions while carrying out the tasks. Upon informing the same to the operator prior to photographing he expressed displeasure on being photographed. The authors did not make any attempts to persuade the operator to change his decision of denial. Instead the authors observed each position the operator ends up while carrying out tasks and one of the author themselves performed the process for photographing the postures for ergonomic analysis. The second principle informed consent refers to the amount information provided to prospective contributors to decide upon their participation during the research study. This was addressed by the authors while scheduling interview/discussion session by informing the participants about the purpose of interview/discussion session, sending in a prior mail that included questionnaire and seeking permission to record the interview/discussion session. Moreover, the participants were given enough time to decide upon their participation and the authors also proposed on being available for interview/discussion session that was convenient for the participants. The third principle harming participants refers to physical harm, stressful harm and harm to self-esteem for both individuals and organisations. Researchers must also regard the confidentiality and anonymity requested by both individuals and organisation with great respect. During the master thesis, it was addressed by the authors by seeking permission from project sponsor always prior to carrying the intended task with regards to confidentiality. The fourth principle deception refers to luring individuals for benefits like money and future employment opportunities. It wasn't applicable during the master thesis **[Ibid]**.

3.5 Research Quality

The quality of the research study can be assessed in different ways depending on the type of research study **[22]**. The authors of the master thesis have considered to use trustworthiness as a basis to access the quality of this research study and it refers to the *credibility, transferability, dependability and confirmability of the research quality* **[Ibid]**. Credibility and internal validity addresses two aspects *'is the research believable?'* and *'are the author's conclusions supported by the research findings?'* **[23]**. To ensure this the authors used a triangulated approach where the objective was to collect and analyze more than one type of data sources. The authors also had regular discussion with primary and secondary stakeholders to ensure that the findings were definitive. Above all the authors have used two well established methodology for the research study. Transferability and external validity addresses two aspects *'is the research applicable to other context and situation?'* and *'can the result be generalized?'*. The put forward solution in the research study solely focus on the process setup by VCC. However, the recommendation can be transferred to all contexts of manufacturing companies with similar processes and moreover VCC should consider the proposed solution for all their manufacturing plants across the globe. Dependability and reliability addresses two aspects *'is the research repeatable?'* and *'does the research yield consistently same results?'* **[Ibid.]**. According to Bryman and Bell to make certain of this aspect can be through storing the material of the research study for auditing **[22]**. All the material is kept as records by VCC. Confirmability and objectivity addresses two *aspects 'degree which the research can be corroborated by others?'* and *'extent which researcher has provided distinct perspective to the research study that affect the results?'* **[23]**. While the first aspect was ensured in the research study by the authors upon investigating the negative instances of the earlier findings, the second aspect was minimized to as much extent as possible by not forming opinions on personal values, beliefs and previous experiences. However, it is impossible to claim that the results were not at all affected by this **[Ibid.]**.

4 Result

This chapter depicts the empirical results established, because of application of the methodologies and tools associated with the methodologies by the authors. It is organized as DMAIC empirical findings and Dynamo++ empirical findings.

4.1. DMAIC Empirical Findings

The following section describes the findings of each phase of DMAIC methodology.

4.1.1 Define

Project charter for the master thesis has been outlaid, which clearly represents a brief overview and organization of the master thesis. This document was looked upon and updated as the phases of the project was completed in the due course of the master thesis, refer Appendix A.

4.1.2 Measure

The development of process map based on observation at VCT plant and study on PII enabled the authors to understand and visualize the flow of the process as in the current state. The PII and process map can be accessed in the Appendix B and Appendix C of the report respectively. The developed fishbone diagram helped the authors to identify main causes along with primary and secondary causes affecting the process outcome, see Figure 13**.** A discussion with stakeholders was conducted to project all the causes and it was decided that the authors must focus on measurement for further analysis. Under measurement the operator is the main cause and blurriness of the beam pattern projected on the board is the primary cause that is limiting the operator to measure and document values, and make adjustment if required to ensure quality check. Hence the measurement was to be improved to obtain reliable results from the process.

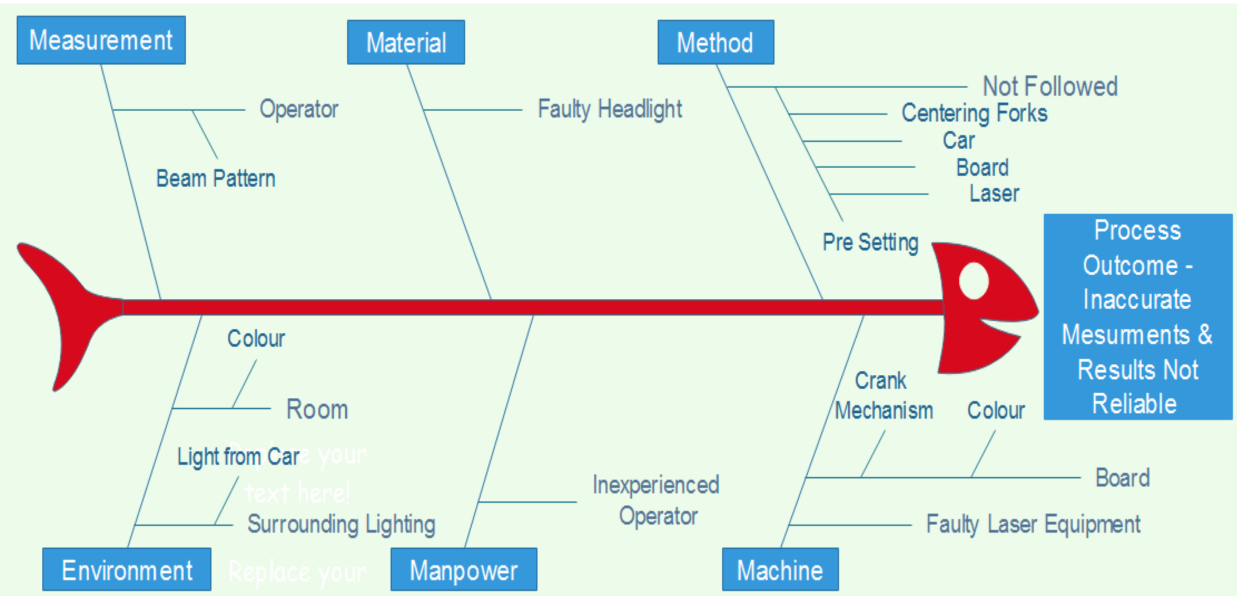


Figure 13: Fish Bone Diagram

Inaccurate measurements and unreliable results of the manual headlight aiming process led the authors to decide upon the planning and execution of the data collection. A data collection was planned to capture the reproducibility/variability aspects of the appraisers. The setting for this data collection at the VCT plant consisted of three operators making the judgment of headlight aiming individually and documenting their assessment in a data collection document. The collected data readings can be seen from the Appendix D. The evaluation procedure is as follows, where each readings of the appraiser combinations were checked and totalled based on four ranges of variation (i.e. same, +/-1, +/-2, +/-3 or more). Each reading of the appraiser combinations is considered to draw conclusions on the amount of variation in terms of height and side assessments of headlight aiming.

- Total number of cars part of the study: 35
- Number of trials: 35
- Total number of individual appraiser readings of height (LHL+RHL): 70
- Total number of individual appraiser readings of side (LHL+RHL): 70
- Number of shifts: 2
- Appraiser 1: Yashwanth (Operator with stipulated training)
- Appraiser 2: Sujith (Operator with stipulated training)
- Appraiser 3: VCT Operator (Experienced Operator)

Table 1 represents three combinations of appraisers and the total number of trials are categorized into four ranges of variation (i.e. same, +/-1, +/-2, +/-3 or more) of both height and side measurements.

Appraiser Combination	**Height**				**Side**			
	Same	+/-1	+/-2	+/-3 or more	Same	+/-1	+/-2	+/-3 or more
Appraiser 1 & Appraiser 2	3	15	19	33	13	22	23	12
Appraiser 1 & Appraiser 3	18	38	8	6	23	26	14	7
Appraiser 2 & Appraiser 3	7	18	31	16	12	22	21	15

Table 1: Results of Appraiser Variation

It is evident from the result that today the number of same measurement between the appraiser combination are very less and there are huge variations between the appraiser combinations in both height and side measurements, which makes the measurement system unacceptable. Hence for VCC to carry out headlight aimining in the best possible method, can only be ensured by improving the process.

4.1.3 Analyze

As part of the analysis phase in DMAIC approach a preliminary qualitative study was initiated by the authors to initiate a literature study. It was followed by an extensive literature study to look for solutions to improve the identified main cause from manual headlight aiming process or to find if any new method can be adopted by VCC that can ensure better quality in terms of headlight aiming. A discussion session was held to validate the findings and, to plan and carry forward improve phase.

Preliminary Qualitative Study

Interview summary of expertise people related to headlights and darkroom process. For questionnaire refer Appendix E.

R&D Engineer

This interview focused on capturing the perspective of R&D engineer at VCC on the possible avenues/areas that could be explored to look out for solution. The expert threw some light on gradient method which according to him helps finding the highest gradient in the light and integrating it as part of a setup thereby helping in better judgment of headlight aiming. The expert also proposed to consider areas of camera and sensors which according to him seemed interesting and promising.

Tooling Engineer

The interview was with the tooling engineer at VCC, the person responsible for implementation of machine and equipment at VCT plant. The discussion covered insights on previous tried solution trials for the process. It was highlighted that possibilities of exploring camera, filters and image processing through photoshop software in pursuit of looking out for solutions is a feasible way to begin the literature study. Also, interesting revelation by the expert during the discussion was the possibilities of using web camera towards real time assessment of headlight aiming.

Active Safety Engineer

The interview with the active safety engineer at VCC, was based on the theme 'headlight and safety'. The expert a shared brief overview on the headlight safety requirements, organizations carrying out evaluation of headlight aiming, procedure associated with the same and demands in the current automotive industry. Interviewee directed the authors on probable solution areas by pointing out the use of Matlab software and algorithms is an option worth exploring.

Literature Study

Summary of alternate solution for the headlight aiming process.

Assistance for the operator to perform task using image processing technique

The edge of objects is shown in the form of sudden change in an image due to change in brightness that varies most greatly **[24]**. Edge are discontinuities in intensity in image processing that can be boundaries of object, boundaries of material properties and boundaries of lighting **[25]**. For the headlamp, it can be interlinked as the dividing line between brightness and darkness region **[24]**. According to the article gradient method can be used to get edge in an image **[Ibid.]**. The solution option constitutes mainly the camera, computer, Matlab software tool (Module - Image processing toolbox) and algorithms as part of the Matlab software, see Appendix F.

Assistance for the operator to perform task using edge detection on a live video stream

This solution option constitutes a web camera, computer, Matlab software tool (Module - Image processing toolbox) and algorithms as part of the Matlab software. "*Image Acquisition Toolbox™ provides a Simulink® block to acquire live image data from image acquisition devices into Simulink models,* see Appendix G*. The Prewitt method is applied to find the edges of objects in the input video stream"* **[26]**.

Optical (photometric) aiming

This solution setup is one that is used for quality testing/auditing the headlamps. It comprises of a light measuring device and a light sensing system, both of which are placed at 25 ft. from the headlamp **[27]**. The light measuring device checks for the correct beam pattern positioning, whereas the light sensing system measures the light gradient. This solution is automatic and employs a light receptor **[Ibid.]**.

Luminoscope

Luminoscope is a digital headlight aiming system generally used for both aiming and auditing headlamps **[28]**. It comprises of a CMOS camera and a unique position check system, algorithms suitable for different headlights and fog lamps. The Camera records and digitizes the headlight image, the unique position check system enables accurate centring of the Luminoscope equipment in front of the headlight. Whereas algorithms aid in testing of headlamps of various country standards like SAE, ECE and different headlamp sources like LED, HID. Other unique feature offered in this equipment is the rail system on the floor which compensates for the variations of the floor and thereby helps in getting accurate results. Last but not the least it offers an optional computer interface and optional alignment laser. Where computer interface enables better visualization of the headlamp image on the computer screen with clear cut-off line and numerical data. The alignment laser helps in accurate alignment of the equipment with the headlamp **[Ibid.]**.

Mechanical Aimers

Mechanical aimer also referred to as beam setters comprises of CMOS camera, glass lens, laser technology, built in display, where CMOS camera aids in capturing image of different headlamp sources like LED, HID and glass lens offers better visibility **[29]**. Laser helps in accurate alignment of the aimer to the headlamp, built in display helps in getting real time image of the light beam and offers possibility of real time measurement of headlamp. Beam setters generally simulate the 10m wall, the lens installed shortens the distance of 10m to 50cm. It offers the flexibility of setting up at any place provided some standard surface requirements are met. It also offers possibilities of software updating to meet the requirements of future lighting systems **[Ibid.]**.

Discussion

This was carried out in the form of focused group discussion with the technical experts relating to headlight and darkroom process at VCC. During the discussion, all the found solutions were furnished in the form of presentation by the authors. The experts validated the solutions and provided input that the most promising solution to improve the current process was ‘Assistance for the operator to perform task using image processing technique and edge detection on a live video stream’.

4.1.4 Improve

Selected criterion and importance rating, Pugh Matrix and physical test results are presented for improvement suggestions in the form of solutions towards implementation, see Table 2, Figure 14 and Figure 15.

Sl. No	Criterion	ME Rating	R&D Rating	Sum of importance rating
1	Quality	5	5	10
2	Accuracy	3	5	8
3	Reliability	5	5	10
4	Cost	1	1	2
5	Flexibility	5	1	6
6	Lead time to introduction	5	2	7
7	Process Time	1	1	2
8	Maintenance	5	2	7
9	Usability, Start up	4	3	7
10	Usability, day to day	4	3	7

Table 2: Selected Criterion and Importance Rating

Pugh Matrix

Concept Selection Legend
Better +
Same S
Worse -

Key Criteria	*Importance Rating*	Benchmark Option	Camera	Web Camera	Optical Photometric Aiming	Luminoscope	Mechanical Aimers
			Solution Alternatives				
Qaulity	10		+	+	+	+	S
Accuracy	8		+	+	+	+	S
Reliability	10		+	+	+	+	-
Cost	2		-	-	-	-	-
Flexibility	6		+	+	S	S	S
Lead time to introduction	7		+	+	-	-	-
Process Time	2		-	S	S	+	-
Maintenance	7		+	+	-	-	-
Usability, Start up	7		-	+	-	+	-
Usability, day to day	7		-	+	-	+	-
Sum of Positives			6	8	3	6	0
Sum of Negatives			4	1	5	3	7
Sum of Sames			0	1	2	1	3
Weighted Sum of Positives			48	62	28	44	0
Weighted Sum of Negatives			18	2	30	16	42
TOTALS			30	60	-2	28	-42

Figure 14: Pugh Matrix Result

From the table above depicting the results of the Pugh matrix, assisting the operator with edge detection on live vide stream (web camera), see Figure 14 and 15, alternative stands out among the other alternative with the highest rating (i.e. based on higher total). The authors further carried out a physical test to validate the top two alternatives and the results obtained is described in detail in the following section.

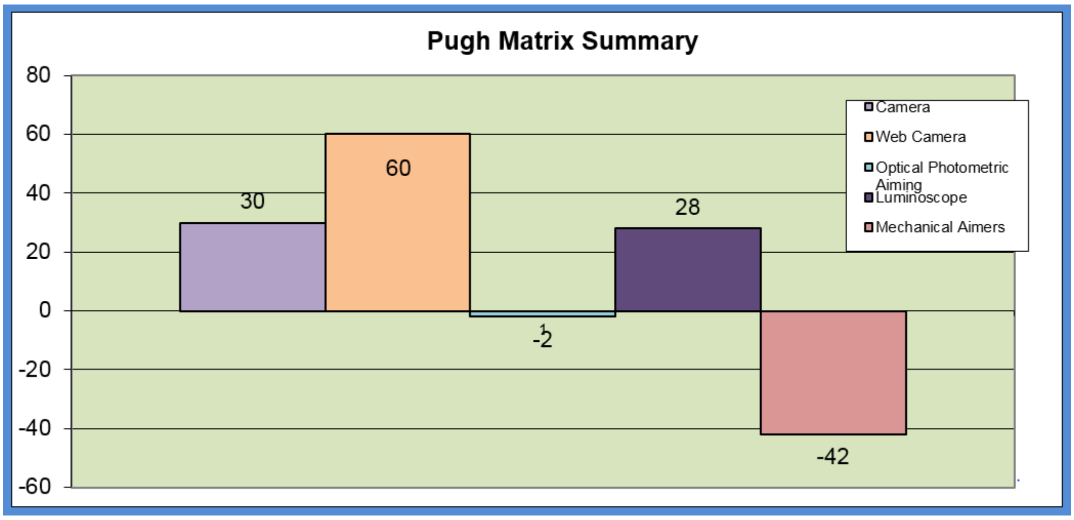


Figure 15: Pugh Matrix Summary

Physical Test

The physical test was based on the two most promising solution that came to view for the authors and stakeholders. The authors captured images and used gradient method for image processing in Matlab software to obtain edges of the headlight pattern. The dividing line between brightness and darkness, which is also referred to as the step edge where intensity change is sudden was obtained **[25]**. It also shows a second line which is the blurry region where intensity change is not instantaneous but rather occurs over finite distance, which is referred to as ramp edge, see Figure 16 **[Ibid.]**. The algorithm used for gradient method can be accessed in Appendix F.

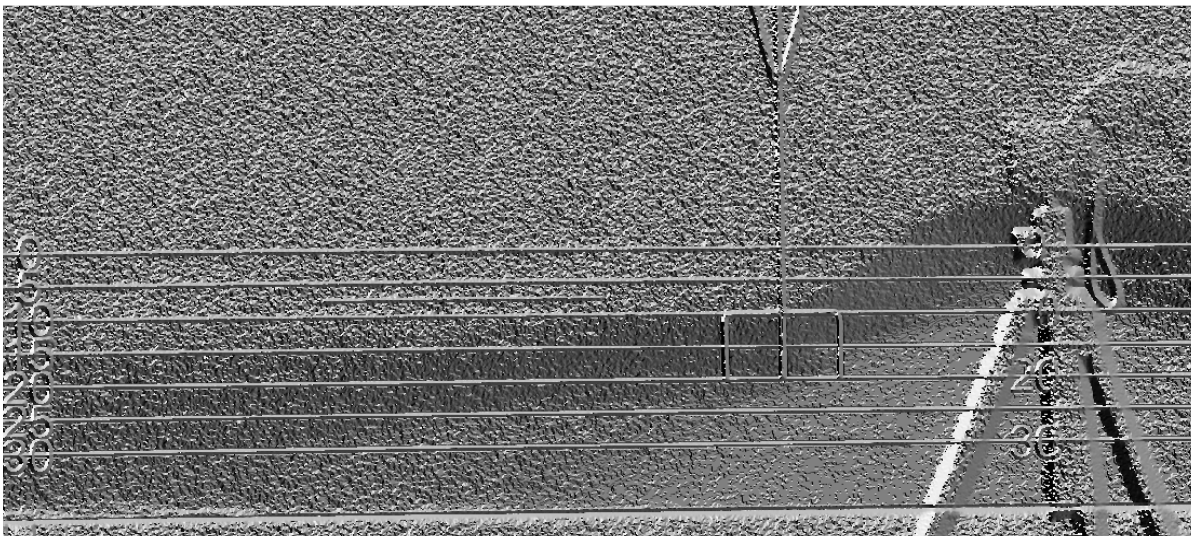


Figure 16: Image Processing Technique

A second physical test was performed by the authors where the improvement solution 'Assistance for the operator to perform task using edge detection on a live video stream' gave similar results to the camera solution, see Figure 17. Simulink® block used to acquire live image data from image acquisition devices can be accessed in Appendix G.

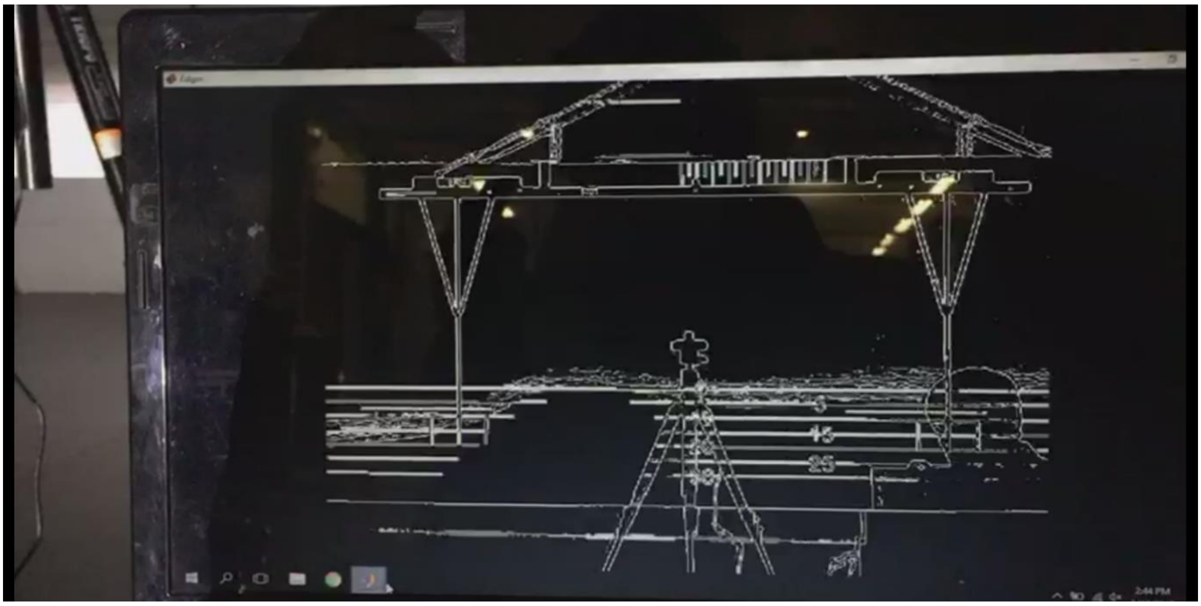


Figure 17: Edge Detection using Live Video Stream

The authors did not carry out the implementation. This step will be reflected in the discussion session for VCC to carry out further tests and take forward the physical implementation at the VCT plant.

4.1.5 Control

The authors did not carry out the control phase since this can be carried out after the successful implementation of the proven solution. This step will be reflected in the discussion section for VCC to monitor and control the suggested improvement for the process.

4.2. Dynamo++ Empirical Findings

The following section describes the findings of each step of Dynamo++ methodology.

4.2.1 Pre-Study

The chosen system for study during the master thesis was manual headlight aiming process based on primary stakeholder requirement, see Figure 3 Section 1.4. Observation of the process at plant led to identifying key parameters listed in Table 3. The process map of the manual headlight aiming process typically represents a top-down flow chart; it was developed to clearly understand and visualize the flow of activities in the process as in the current state. It can be accessed from Appendix C. This completed the pre-study phase.

Sl. No	Parameters	Notes
1	No of operator	1 for each shift
2	No of shifts in a day	3
3	No of working days in a week	5
4	Total no of tools used	2
5	Posture based Ergonomic risks	5
6	Bottleneck	Operator
7	Process time for a product	2-3 minutes

Table 3: Identified Parameters

4.2.2 Measurement

A HTA was developed for the process based on the activities carried out in the pre-study phase, see Figure 18. The manual headlight aiming process consisted of four main tasks and seven sub tasks. The sub tasks were further broken down for each operation carried out by the operator depending on the level of details required for the study. All the tasks identified for the process were assigned a value from the range of one to seven in both physical and cognitive level, refer Appendix H. The assigned values were then input to the LOA matrix shown in the Figure 19. In the current state, all the 22 operations associated in the process are under the human assembling and monitoring. In the process 19 operations obtained 1 in both physical and cognitive level and 3 operations in the process obtained 2 for physical level and 1 for cognitive level respectively.

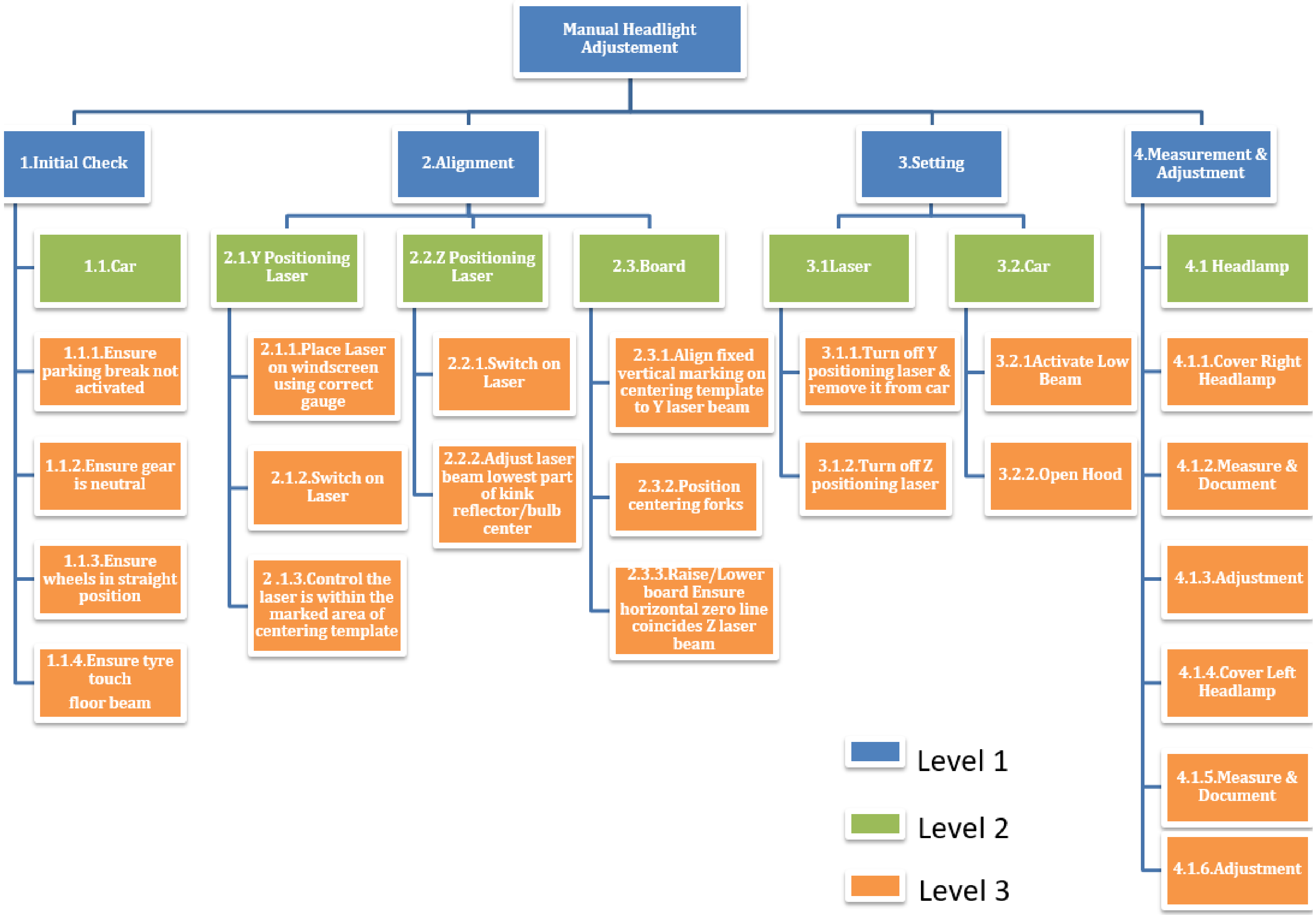


Figure 18: HTA for Manual Headlight Aiming Process Current State

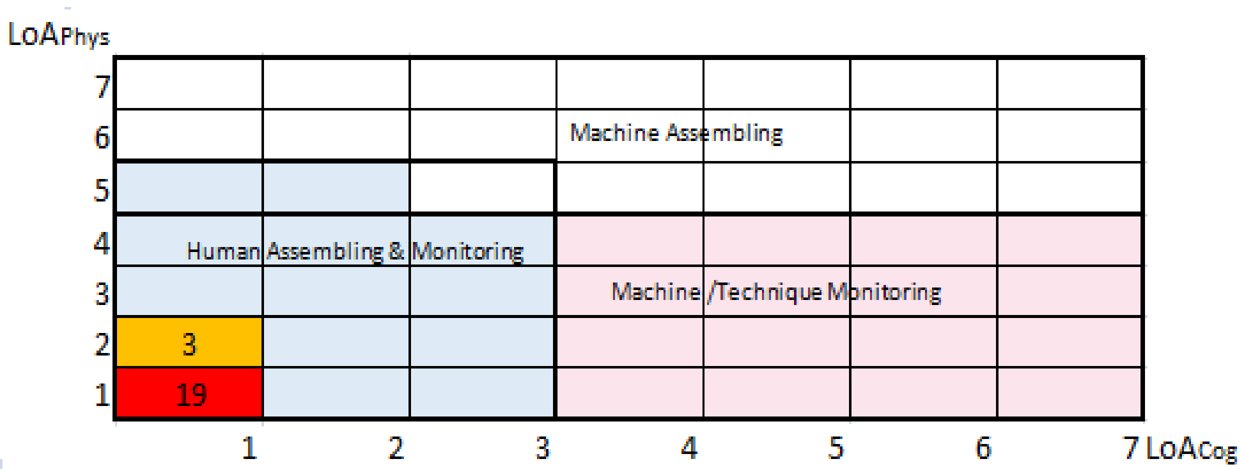


Figure 19: LoA Matrix for Manual Headlight Aiming Process Current State

A posture based analysis was carried out through the rapid entire body assessment (REBA) tool. All the identified risk postures are listed below with the REBA score in the Table 4. The pictures of posture based risk for the tasks and detailed view of REBA analysis for taks listed in the Table 4 can be accessed in Appendix I.

Sl. No	Task	REBA Score
1	Board Adjustment	6
2	Fork Adjustment	3
3	Horizontal Laser Alignment	7
4	Vertical Laser Alignment	8
5	Light Adjustment	2

Table 4: REBA Score for Postured Based Risk

A 'NASA TLX' tool was used by the authors where two operators associated with the process were briefed about the tool and asked to provide input by rating the six criteria of physical and cognitive loading and, support, refer Appendix J. Based on the rating by the operators scores were obtained for the six criterions rated by the operators, see Figure 20 and Figure 21**.** The results were documented in the report that completed the measurement phase.

Figure 20: NASA TLX Scores obtained for Operator 1

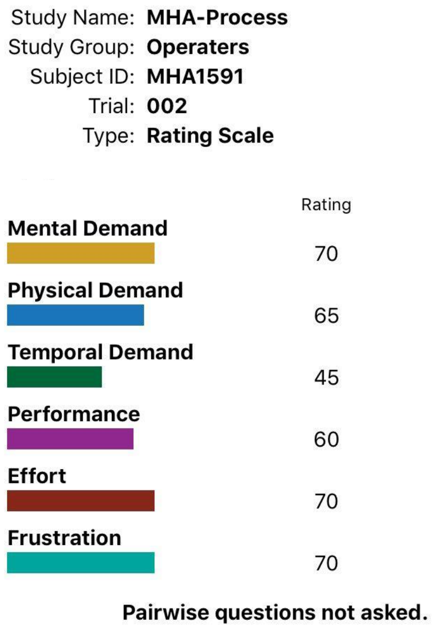


Figure 21: NASA TLX Scores obtained for Operator 2

4.2.3 Analysis

This phase was carried out by a discussion session to decide LoA max and min, followed by designing SoPI for manual headlight aiming process and finally, analysis of SoPI based on task optimisation. The trigger for change for analysing the process was initially defined by the stakeholders. These were quality for the process and improved ergonomics for the operator.

Discussion to decide LoA Max and Min

A discussion session was held that included several primary stakeholders i.e. manufacturing engineers from VCC, master thesis supervisor from Chalmers University of Technology the secondary stakeholder and the authors themselves to decide the maximum and minimum level for each operation in the process.

- ***Sub Task 1.1: Car (Task 1: Initial Check)***

  Two operations from 'Sub Task 1.1: Car' were decided to be fully automated both in physical and cognitive levels from the perspective of improving method to achieve high quality in the process. The minimum and maximum level for these two operations were set to a high value of 7 in both physical and cognitive level, see Table 5 and Table 6.

LoA_{Phys}	1.1.1	1.1.2	1.1.3	1.1.4
7			M	M
6				
5				
4				
3				
2				
1	M	M		

Table 5: Physical LoA Max and Min levels

LoA_{Cog}	1.1.1	1.1.2	1.1.3	1.1.4
7			M	M
6				
5				
4				
3				
2				
1	M	M		

Table 6: Cognitive LoA Max and Min levels

- ***Sub Task 2.1: Y Positioning Laser (Task 2: Alignment)***
- ***Sub Task 2.2: Z Positioning Laser (Task 2: Alignment)***
- ***Sub Task 2.3: Board (Task 2: Alignment)***

  One operation from 'Sub Task 2.1: Y Positioning Laser' was decided to be automated in physical level of 5 and cognitive level to 7. One more operation of the same sub task was decided to move both in physical and cognitive levels to a scale of 7, see Table 7 and Table 8.

  The operation of aligning the horizontal laser to lowest part of kink reflector/bulb centre from 'Sub Task 2.2: Z Positioning Laser' was decided to set a scale of physical level 2 and cognitive level 1, see Table 7 and Table 8.

  The last operation is the adjustment of the board from the 'Sub Task 2.3: Board'. This operation was decided to reach a scale of physical level 4 and the cognitive level 1, see Table 7 and Table 8.

LoAPhys	2.1.1	2.1.2	2.1.3	2.2.1	2.2.2	2.3.1	2.3.2	2.3.3
7			M					
6								
5	M							
4								M
3								
2					M			
1		M		M		M	M	

Table 7: Physical LoA Max and Min levels

LoACog	2.1.1	2.1.2	2.1.3	2.2.1	2.2.2	2.3.1	2.3.2	2.3.3
7	M		M					
6								
5								
4								
3								
2								
1		M		M	M	M	M	M

Table 8: Cognitive LoA Max and Min levels

- ***Sub Task 3.1: Laser and Sub Task 3.2: Car (Task 3: Setting)***
  All the operations of 'Sub Task 3.1: Laser' and 'Sub Task 3.2: Car' were decided to be kept same in both cognitive and physical level as in the current state. LoA min and max for the 'Task 3: Setting' was completely closed and not developed.

- ***Sub Task 4.1: Headlamp (Task 4: Measurement & Adjustment)***
  Two operations from 'Sub Task 4.1: Headlamp' was decided to be kept on a scale of 5 in physical level and cognitive level 2 to help the operator carry the task. All other operations will remain at same level as in the current state, see Table 9 and Table 10.

LoAPhys	4.1.1	4.1.2	4.1.3	4.1.4	4.1.5	4.1.6
7						
6						
5		M			M	
4						
3						
2			M			M
1	M			M		

Table 9: Physical LoA Max and Min levels

LoACog	4.1.1	4.1.2	4.1.3	4.1.4	4.1.5	4.1.6
7						
6						
5						
4						
3						
2		M			M	
1	M		M	M		M

Table 10: Cognitive LoA Max and Min levels

Design of Square of Possible Improvements (SOPI)

The SoPI for the complete process was designed and input into the LoA matrix based on the decided minimum and maximum level during the discussion session conducted in the previous step. It can be seen in the Figure 22 below.

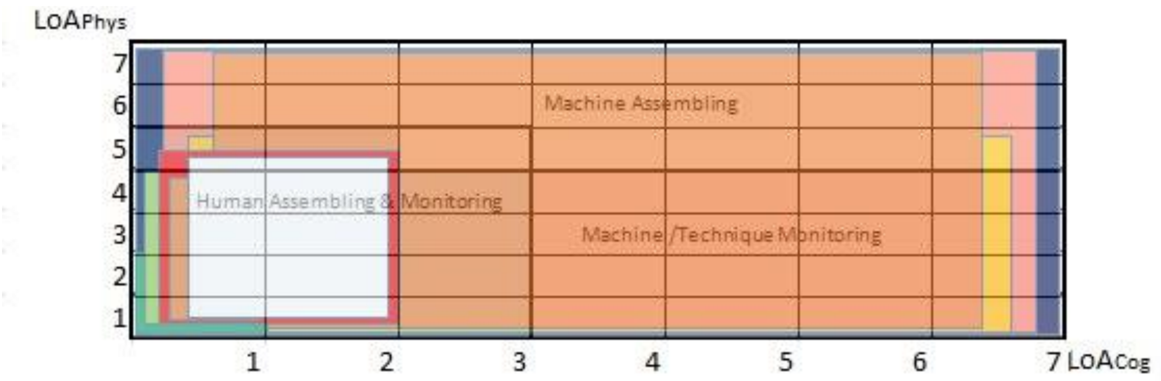


Figure 22: SoPI for Manual Headlight Aiming Process

Analysis of SoPI and Improvement Thoughts

SoPI's based on task optimisation were developed for each task and improvement thoughts are listed below to realize task elevation.

- ***Sub Task 1.1: Car (Task 1: Initial Check)***

  The improvement suggestion discussed was to use car centring platforms to align the cars in a straight position as well as to ensure that it touches the floor beam. The operations are improved to physical and cognitive level of 7, see Figure 23.

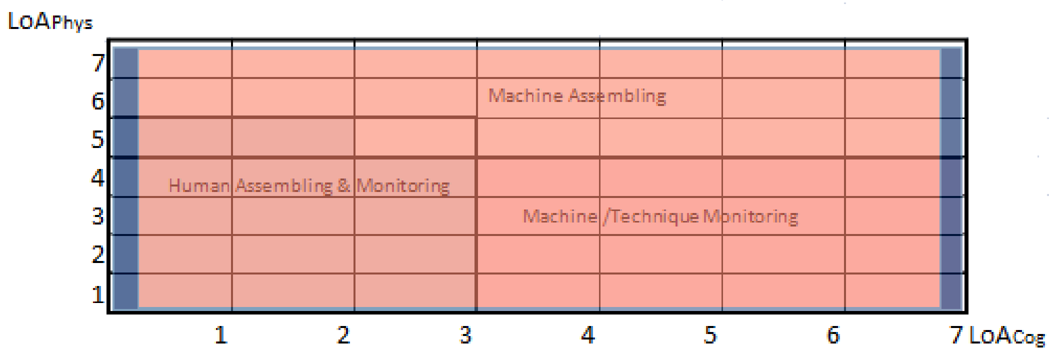


Figure 23: SoPI Task 1

- ***Sub Task 2.1: Y Positioning Laser (Task 2: Alignment)***
- ***Sub Task 2.2: Z Positioning Laser (Task 2: Alignment)***
- ***Sub Task 2.3: Board (Task 2: Alignment)***

  The improvement suggestion realized was to mount the Y positioning laser on the upper wall of the darkroom. It enables to achieve a physical level 5 and cognitive level 7 and, physical level 7 and cognitive level 7 respectively for the two operations, see Figure 24.

  Improvement can be realized with use of a static tool to a physical level 2 whereas the cognitive level 1 will remain the same. In this case, the static tool is a fixture that must be developed so that when mounted on headlight will have a marking on it to align the Z positioning laser, see Figure 24.

  Improvement suggested was to help the operator carry out the task by automated hand tool a physical level 4 whereas cognitive level 1 is kept the same as in the previous state. In this case, the automated hand tool is a board that can move up and down by pressing a button, see Figure 24.

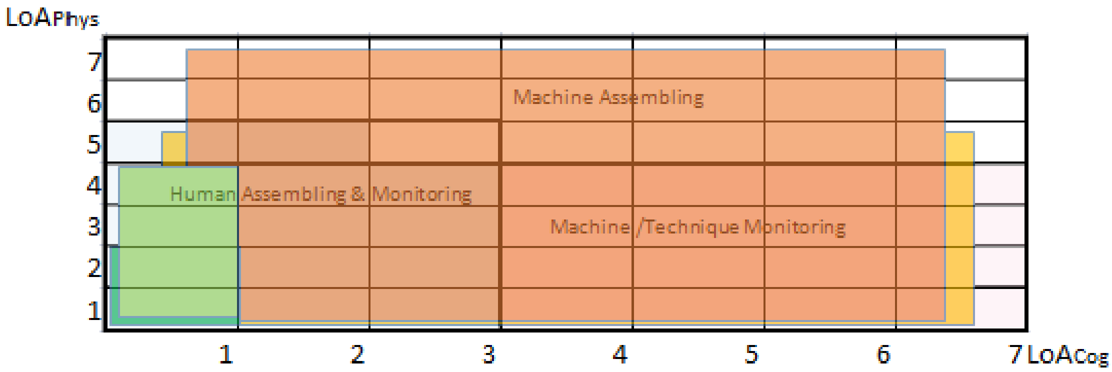


Figure 24: SoPI Task 2

- ***Sub Task 4.1: Headlamp (Task 4: Measurement & Adjustment)***

  The measurement and documentation can be improved to physical level 5 by enabling the operator with a static machine work station that includes a camera/web camera and computer whereas in the cognitive level it can be increased to level 2 that will help the operator in decision making, see Figure 25.

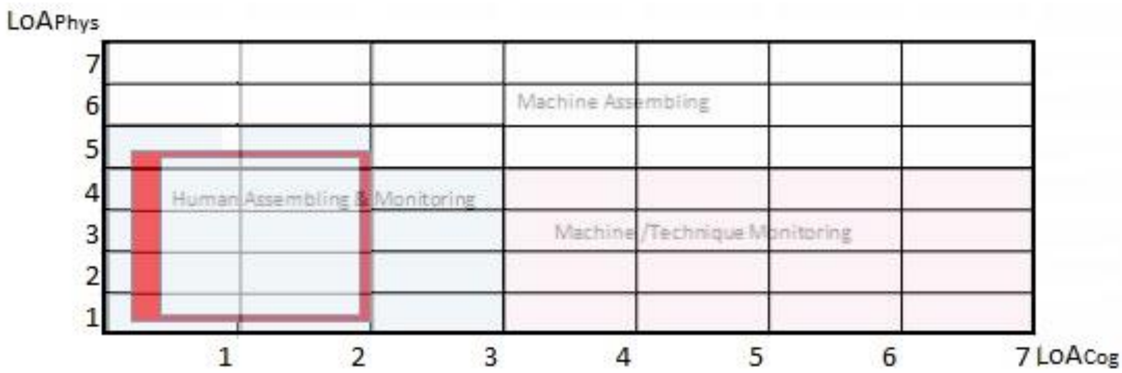


Figure 25: SoPI Task 4

4.2.4 Implementation

In the last phase of the Dynamo++ only one step was completed to project result for primary and secondary stakeholders. The remaining steps must be carried out by the primary stakeholder VCC. Results are presented below.

Visualise suggestions of improvements

Based on the improvement suggestions discussed in the previous step and, company's wishes and demands a future state LoA Matrix, see Figure 26 and HTA, see Figure 27 were developed to depict the new process the operator must carry out and, the operations physical and cognitive level in the future state.

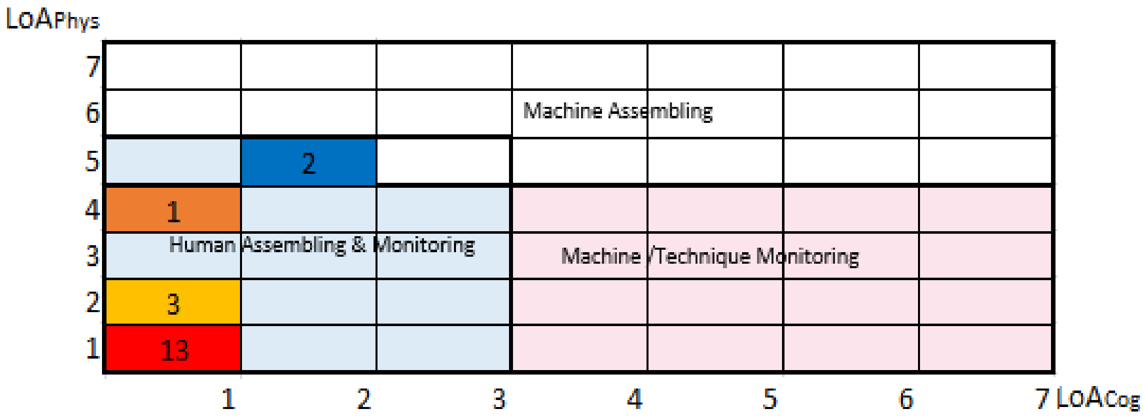


Figure 26: LoA Matrix for Manual Headlight Aiming Process Future State

The result is that operations requiring a physical and cognitive level of 1 are reduced to thirteen, one operation reaches a physical level of 4 and cognitive level of 1 and two operations are elevated to physical level of 5 and cognitive level of 2. It should also be noted that 3 operations are completely removed from the process in the future state i.e. total number of operations is 19 as compared to 22 in the current state when the LoA was documented in the measure phase, see Figure 19.

The last two steps of the Dynamo++, implementation of the chosen suggestions and following-up when the suggestions have been implemented was not carried out by the authors. These steps will be reflected in the discussion session for VCC to take forward and carry out the steps to automate the process to achieve high quality for the process and improved ergonomic condition for the operator.

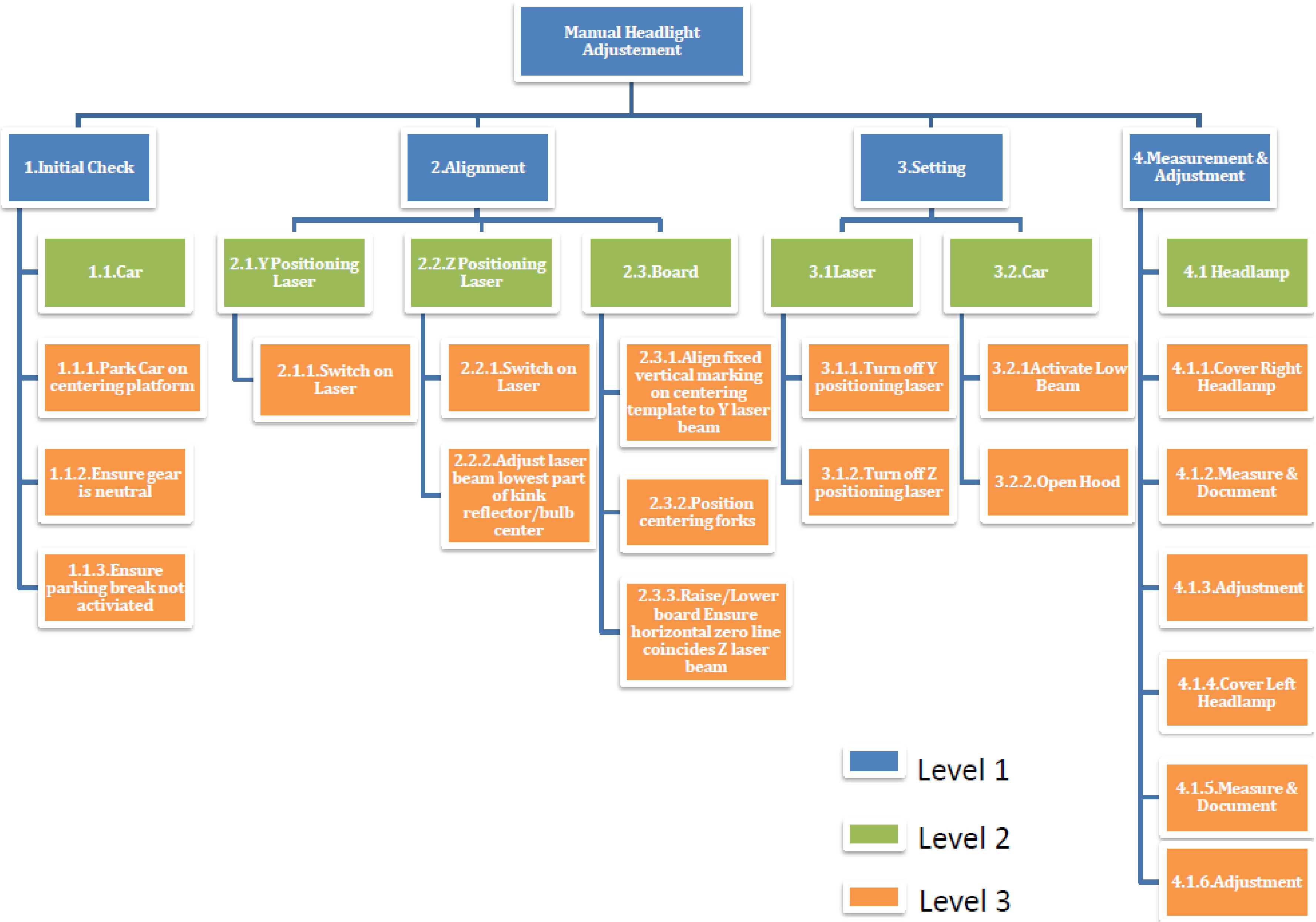


Figure 27: HTA for Manual Headlight Aiming Process Future State

5 Discussion

This chapter depicts the discussion on arrival of solution, about the scientific methodologies used, discussion on relating the process under study to theoretical concepts referred by authors and addresses the social sustainability considered during the master thesis.

5.1 Optimized Method

The arrival at optimized method as solution to help VCC carry out quality audit process of headlight aiming was realized through both DMAIC and Dynamo++ methodologies. DMAIC suggests that assisting the operator to carry out the task using edge detection on live video stream offers the benefit of real time assessment and adjustment of headlight aiming as the optimized method. But it is of utmost necessary to carry out more test trials and over a period to understand and judge the reliability and, stability aspects of the new solution option before physical implementation at VCT plant by VCC. Dynamo++ suggests automation improvement solutions to realize further improvements in achieving optimized method in terms of having the process more towards achieving higher quality, accuracy and reliability. While the solutions suggested from the application of both methods individually will drive improvements in their way, combining the results of both methodology will ensure VCC has the best optimized method for carrying out quality audit process of headlight aiming.

5.2 Application of DMAIC in this Master Thesis

DMAIC one of the continuous improvement methodology is the most sought out method for realizing improvement in industries to stay competitive in the market **[6]**. Aartsengel and Kurtoğlu in this context makes a relative statement addressing the companies to look upon methods like DMAIC as a business investment that adds value in long term **[Ibid.]**. Overall this methodology of DMAIC in the framework of this master thesis helped realizing an optimized method as solution and laid foundation for continuous improvements in the various aspects of the process in the future.

In this study, the methodology was adopted to achieve the purpose of the master thesis. The fishbone diagram helped the authors to list all the probable cause affecting the outcome, but the twofold reason led the authors to narrow down and investigate only the measurement category. The first reason was the concerning fact for VCC from the beginning of the master thesis study i.e. individual judgement of the headlight aiming leading to unreliable results, the other reason was that VCC had taken care of certain categories and ensured that aspects under those categories were being investigated by VCC's internal team. The measure phase also involved capturing the comprehensive information of the problem in current state through data collection. Although the development of a process map showing the process steps in detail and a fishbone diagram identifying probable causes affecting the process outcome would have been deemed sufficient, the measure phase lacked numerical data backing for quantifying the current state. Moreover, Shankar also substantiates the need for collecting numerical data in the current state and compare the same with quantifying results when the improvements have been made in the future state **[13]**. This also helps to display the improvements clearly to the stakeholders **[Ibid.]**. For this the authors carried out data collection study limiting to capture the reproducibility aspects of the operator, as it was the most significant cause affecting the process outcome and obtained the numerical data depicting the current state.

In this context during analyze phase, as part of the triangulated approach a quantitative study was deemed unnecessary, which is because the target audience with the knowledge of the process were limited. Although it can be argued that such a study would have offered the authors to capture another dimension of the process and its improvement, the use of at least more than one type of data sources in thesis can counterattack the argument **[15]**. Also, the subjective implications of the audience with limited or no knowledge of the process would not be value adding input to the master thesis and time consuming is what the authors concluded. Finally, this aspect was tackled through qualitative study through interviews and discussion session with the technical experts at VCC which formed a solid base for validation.

The fourth phase of the methodology includes realizing the improvements with aid of tools like Pugh matrix and physical implementation of the same. Initially improvement suggestions were evaluated using the Pugh matrix with a set of significant criteria decided together with stakeholders at VCC from which assistance for operator using web camera emerged as most promising alternative. Also, physical testing was carried out by the authors using both camera and web camera alternative and results were compared, where it was seen that both the alternatives gave similar results. Moreover, the physical test was conducted in presence of experts with knowledge in headlight, darkroom process and image processing techniques who also validated the findings. Other important aspect to discuss is the other motivation behind the choice of web camera solution, for instance the solution option of Luminoscope with a comparatively high Pugh matrix score of 28 offers the flexibility of an automated solution, but creates a bigger question on maintenance and calibration needs that again highlights the current concern of VCC on the need for reliable input for calibrating the automated headlight aiming equipment in EOL production system at VCT Plant. Implementation not being part of the scope in the master thesis is the next step VCC must carry out. Before implementing the suggested solution, VCC must audit internally for its robustness by running a trail batch during production.

Generally, the last phase of the DMAIC approach includes suggesting action plan for monitoring the solution in future together with development of work instructions towards standardizing the new process. This phase was not executed in this master thesis because it is very much necessary for the solution to be implemented to carry out this phase. Hence a suggestion of measurement system analysis study and development of work instruction to monitor and control the process is suggested for VCC. Although it can be argued that work instructions could have been developed in the thesis based on the physical test it is of very much importance to consider design principle for information presentation (DFIP) to create work instruction in this case **[30]**. It is because the suggested improvement of assistance for the operator using web camera or image processing technique requires considerable technical knowledge for the operator to use it. Hence both written and oral instructions i.e. work instructions must be developed considering usability and cognitive ergonomics into picture. If not, the operator will make errors during the process and quality cannot be achieved **[Ibid.]**. Hence the authors suggest VCC to consider the DFIP when developing and incorporating new work instructions into their PII for manual headlight aiming process.

5.3 Application of Dynamo++ in this Master Thesis

Dynamo++ was adopted in the master thesis by the authors to achieve the stakeholder's requirement. Moreover, this methodology facilitates a process towards automation improvement based on triggers for change **[10]**. According to Dencker et al. processes in final assembly at manufacturing companies generally falls in the human assembly and monitoring **[11]**. The manual headlight aiming process termed as 'darkroom process' by VCC in the current state clearly falls in the human assembly and monitoring. All the operations to be carried out by the operator during the process in the suggested future state as seen in the results section, also falls in the human assembly and monitoring. The main difference between the current state and future state is that the total number of operations are reduced and certain operations are elevated to a higher physical and cognitive level which falls within the window of 5 in physical level and 2 in cognitive level as suggested for final assembly stations, see Figure 7. The improvement suggestions realized during the study improves the quality of the process and ergonomic conditions for the operator. Automation improvements will lead to proactive behavior of the processes in the production system. Also, the changes in information and competence level are enablers for increasing system performance by reducing process time, lead time and down time according to Dencker et al. Theoretically it can also be claimed that process time also reduces significantly with the implementation of the suggested improvements in the thesis **[Ibid.]**. Hence the thesis work conveying such results Dynamo++ can be regarded as a good methodology for manufacturing companies to increase the level of automation for the processes in their production system.

Certain steps in the methodology were adopted in a different manner than the regular method with the integration of various tools as per the requirement during the master thesis by the authors. In the pre-study phase a VSM was not developed as the study did not focus on the production system of the complete EOL at VCT plant, but solely focused on one of the process. Hence the process map used to realize the step can be justified as Dynamo++ can be integrated with various tools **[10]**.

During the measure phase REBA tool was used to analyze posture based risk as it focuses on entire body and also is regarded as quick tool to conduct ergonomic evaluation **[12]**. Although certain tasks have a high REBA score as seen in the result section indicating a need for minimizing the risk for the operator, it may be regarded as limitation in the master thesis as the exposure time and accumulating loads for the tasks are not considered during REBA analysis **[Ibid.].** This was very much evident during the thesis as VCC have 'Make to Order' production approach. This means if the same models of cars reached the process the operator did not carry out certain tasks. The failure of repetitiveness in performing tasks limits the results. Hence the authors after the consultation with the expert related to social sustainability and human factors/ergonomic in production systems used a NASA TLX to measure the physical and metal workload for the operator. Two subjects were chosen that included an operator who has been carrying out the process for six months, every day one shift and the other operator who has carried out the process for two years, two shifts per week during the functioning time of VCT plant. As seen in the results both the answers varied highly. Moreover, due to varied answers by the operators the pairwise questions were not asked during the study. The 15 pairwise questions will account for obtaining the weight rating for each of the six criterions on a scale of minimum 0 to maximum 5 **[20]**. Each criterions weight rating is multiplied by the scale rating given by the operator. All the six criterions values are then summed up and divided by 15 to get average workload for the workplace/process **[Ibid.]**. Nevertheless, it can be concluded that the process must be subject to deeper ergonomic analysis through NASA TLX method by considering larger number of subjects carrying out the process in all VCC production plants. The further investigation will help VCC to create better physical and cognitive conditions for the operator by considering the automation improvement solutions suggested in the thesis, as the work postures and the environment associated with the process are important for the reaching high efficiency and, quality in executing the task **[12].**

In the analysis phase a workshop was not conducted, rather a discussion session was held to decide the maximum and minimum levels for physical and cognitive automation. A workshop will include all the stakeholders right from operators, supervisors at the plant to engineers from management associated with the process. Moreover, conducting a workshop might have led to different levels of realization of the maximum and minimum levels. It is because brainstorming leads to more optimized realization of the maximum and minimum levels during a workshop. During the analysis of SoPI, two possible SoPI's can be designed depending on the requirement i.e. SoPI operation optimization or SoPI task optimization **[17]**. An operation optimization ensures that all the tasks in the process can be moved to one square of possible improvements that reduces complexity of automation between each task in the process and easy for the operator to carry out the process. Task optimization ensures that each individual task can be independently moved to the required level of improvement based on the trigger for change, but this has a limitation that complexity of automation between each task in the process is increased due to varying levels in the automation and it may reach an outcome of high difficulty for the operator to carry out the process. This might lead to a future state, where the process for the operator might be confusing **[Ibid.]**. Nevertheless, the authors used a task optimization over operation optimization to realize the improvement suggestions. The use of task optimization can be justified as the suggested future state doesn't have much varied automation levels for operations in the process and hence it can be regarded as good improvement suggestions.

Due to the delimitations set in the master thesis the last steps of the implementation phase where the physical implementation takes place and measuring the results was not carried out by the authors. Hence suggested improvements can be subjective to variation in the study when it comes to actual implementation.

Discussion on Suggested Improvements

Use of car centering platforms helps in achieving surface level, straight parking of the cars and right parking distance required for manual headlight aiming process, which are the foremost prerequisite for headlight aiming using manual method. It improves the quality achieved for the operations in the process as slight variation in not parking the car straight and to the required distance might lead to varied aiming and adjustment of the car headlights in the process.

Mounting vertical laser on upper wall will ensure risk free posture for the operator to carry the operation as the current posture obtains a REBA score of 8 as seen in results chapter that indicates high risk and must be further investigated and implement change for the operation. Moreover, all the operations can completely be eliminated, but the operation of switching on the laser is kept in the future state to ensure that the previously suggested improvement of using car centering platform is working correctly over time. It must be noted that this improvement can only be achieved because of the previous suggested improvement.

Fixture suggestion will improve the easiness for the operator to achieve the operation. Although it has ergonomic issues in the current state with the posture obtaining a value of 7 on REBA analysis as seen in results chapter it cannot be improved. Only quality can be ensured to improve as in the current state it is difficult to ensure that the right quality is achieved.

Suggested improvement of implementing a board that moves up and down by pressing the button ensures quality of the process as well as improved ergonomic condition for the operator. It is because the operation in the current state obtains a REBA score of 6 as seen in results chapter that indicates high risk and must be further investigated and implement change and, moreover the quality in the current is bad as the board has high variation due to its complicated settings in aligning it to desired state.

The suggested improvement to use camera/web camera and computer for measuring and documenting helps the operator to achieve the quality demanded by the process.

5.4 General Discussion of Theoretical Concepts

Production System

Production system which is synonymous to a transformation system converts input to output, connecting this production system's perspective to the context of a process as described by Harrington can be related to manual headlight aiming process **[3]**. The input is the car arriving for the quality check headlight aiming, the intermediary evaluation procedure with measuring the aiming and adjustment constitutes to the transformation phase and finally optimally aimed headlights is realized as output.

Also, as structural perspective of a production system comprises of different elements and interrelation between them **[Ibid.].** It is totally apt and relative in this master thesis, as the manual headlight aiming at 'darkroom process' workstation and the automated headlight aiming equipment in the WAE station of EOL production system at VCT plant form the elements of the whole structure of headlight aiming process. The interconnection between the process can be seen where output from 'darkroom process' workstation is given as input to another system i.e. automated headlight aiming equipment in the EOL production system at VCT plant.

Quality

This forms the backbone/trigger for both the DMAIC and Dynamo++ approaches taken in this master thesis and therefore forms the core of this study. Quality with its omnipresence in every aspect of industry including in the context of process ensures better control over the processes enabling reliable outcomes from the processes **[4]**. Connecting to the quality management circles a combination of principles (focus on process, continuous improvement) + tools (cause and effect diagram, process map) + methodologies (DMAIC, benchmarking) has helped in realizing the improvement in the form of new solution alternative with high quality, reliability and stability towards assessment of headlight aiming **[Ibid.]**. Although it can be argued that other combination could have been used to realize the improvement in this master thesis, DMAIC has been found to be the most effective methodology to solve open problems in manufacturing and service industries **[31].** Also in the Dynamo++ approach with quality as trigger for change the authors proposed suggestion for increasing the level of automation of certain operations in the process with quality as top priority, all of which contributes to making the process more reliable, stable and robust. Therefore, quality formed the premise for the start, remained important in due course of the master thesis and will be so in the future.

5.5 Social Sustainability

This master thesis with the development of optimized method as a suggestion for accurate headlight aiming following two approaches namely DMAIC and Dynamo++ has considered various aspects of improvements with the trigger of quality. In the aspects of DMAIC by improving the process the master thesis has enabled the operator for easier and accurate judgement of the headlight aiming by providing assistance through camera/web camera as part of the setup of the new process. This improvement was realized considering the human in the system being able to carry out the process with the technological assistance **[12]**.

In the aspects of Dynamo++ the authors have evaluated the existing process and suggested increasing the level of automation of certain operations in the process with quality and ergonomics as trigger for change towards increasing the efficiency and, accuracy of the process. The ergonomic evaluation carried out on the work tasks in the process has also given due consideration towards making the workplace safe and healthier for the operator in the long run. Thus, making the process on a whole as socially sustainable, meeting the needs of the current members of the process as well as supporting the future generation in carrying out the process in a healthier way, which is totally in line with the definition of social sustainability by the United nations world commission on environmental and development (WCED) "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" **[32]**.

5.6 Suggestions for Future Study

As part of the thesis, further research areas that VCC should consider exploring are:

- In the current state, it was impossible to detect the extent to which the parking of car in misaligned position will have an impact on the process. Investigating this aspect will give more credibility for VCC to consider the implementation of automated improvement solutions suggested.
- Camera calibration which corrects the distortion in lens was not considered by the authors as the research findings suggested that the camera will not have any effect on the process. However, it is good to further investigate the same.
- Today's fast growing electronic world offers various vision cameras that are more precise and are integrated as part of the Matlab software for image acquisition. Testing this might yield better real-time measurement and adjustment achieving higher quality for the process.
- VCC must regard testing the suggested solution not only at VCT plant but across all their plants throughout the world to see if it yields same results over time and to analyze the robustness of the setup.
- The economical aspect was not addressed in the thesis. Hence to implement the automation improvements suggested which basically improves both quality and ergonomics, the cost benefit analysis should be carried out.

6 Conclusion

The master thesis study focussed on analysis to increase the operations efficiency of a process in a production system. This chapter depicts the main highlights of the master thesis study.

It can be concluded that the authors successfully achieved the purpose of the thesis to help VCC improve the quality of headlight aiming of cars. The operations efficiency realised through established methodology in this master thesis study can also be referred by individuals when focusing on continuous improvement for a process. As an end note the bulleted points below gives the main highlights of the master thesis.

- Improved headlight aiming process realized through DMAIC, thereby offering better judgement of headlight aiming by aiding the operator using edge detection on live video stream.
- Improved quality, reliability and accuracy for the process upon realisation of automation improvement solutions through Dynamo++.
- More accurate input can be provided to calibrate the automated headlight aiming equipment in WAE station of EOL production system at the VCT plant.
- Reduced variability aspects of operator/individual in assessment of headlight aiming.
- Optimized method offers an array of other multiple advantages like reduced process time, increased efficiency and flexibility.
- Optimized method can be reflected on a global scale, where a similar process is set up by VCC at their manufacturing plants. Moreover, the solution suggested is a cheap solution in terms of cost and, easy and quicker to implement from manufacturing engineering point of view.
- The suggested optimized method can also be replicated at various testing procedures of headlight aiming within VCC.
- If the recommended solutions are implemented, VCC can have a common process across all their plants. It can be concluded in such a case that the process can be controlled and monitored on a global scale.
- The thesis addressed sustainability aspects by taking social, and environmental aspects into consideration. The social and environmental aspect was covered by the automation study to argue for creating better working conditions for the operator.

7 References

[1] "Company Information | Volvo Cars", *Volvocars.com*, 2017. [Online]. Available: http://www.volvocars.com/intl/about/our-company/our-company-at-a-glance. [Accessed: 28- May- 2017].

[2] B. Wu, *Manufacturing Systems Design and Analysis: Context and Techniques.* London: Chapman & Hall, 1994.

[3] M. Bellgran and K. Säfsten, *Production Development: Design and Operation of Production Systems.* London: Springer, 2010;2009;

[4] V. Siva, "Introduction to Quality Management", Lecture Material, Chalmers University of Technology, 2016.

[5] "Continuous Improvement Model - Learning Resources| ASQ", *Asq.org*, 2017. [Online].Available:http://asq.org/learn-about-quality/continuous-improvement/overview/overview.html. [Accessed: 28- May- 2017].

[6] A. Van Aartsengel and S. Kurtoğlu, *A Guide to Continuous Improvement Transformation*. Berlin, Heidelberg: Springer, 2013.

[7] C. Madu, *Handbook of total quality management*. Dordrecht [u.a.]: Kluwer Acad. Publ, 1998.

[8] M. Groover and G. Jayaprakash, *Automation, production systems, and computer-integrated manufacturing*.

[9] Å. Fast-Berglund, "Automation Strategies and Levels of Automation", Lecture Material, Chalmers University of Technology, 2015.

[10] Å. Fasth, "Quantifying Levels of Automation - to Enable Competitive Assembly Systems", Ph.D., Chalmers University of Technology, 2012.

[11] K. Dencker, Å. Fasth, J. Stahre, L. Mårtensson, T. Lundholm and H. Akillioglu, "Proactive assembly systems-realising the potential of human collaboration with automation", *Annual Reviews in Control*, vol. 33, no. 2, pp. 230-237, 2009.

[12] C. Berlin and C. Adams, *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance.* London: Ubiquity Press, 2017.

[13] R. Shankar, *Process improvement using Six Sigma*. Milwaukee, Wis.: ASQ Quality Press, 2009.

[14] "Fishbone Diagram (Ishikawa) - Cause & Effect Diagram | ASQ", *Asq.org*, 2017.[Online].Available:http://asq.org/learn-about-quality/cause-analysis-tools/overview/fishbone.html. [Accessed: 29- May- 2017].

[15] C. Berlin, *Project PM - The META conference PPU215: Research Methodology in Production Projects*. Gothenburg: Chalmers, 2016.

[16] L. Lønmo and G. Muller, "7.1.2 Concept Selection - Applying Pugh Matrices in the Subsea Processing Domain", *INCOSE International Symposium*, vol. 24, no. 1, pp. 583-598, 2014.

[17] Å. Fast-Berglund, J. Stahre and K. Dencker, "Measuring and analysing Levels of Automation in an assembly system", in *The 41st CIRP Conference on Manufacturing Systems*, Tokyo, Japan, 2008.

[18] A. SHEPHERD, "HTA as a framework for task analysis", *Ergonomics*, vol. 41, no. 11, pp. 1537-1552, 1998.

[19] S. Hignett and L. McAtamney, "Rapid Entire Body Assessment (REBA)", *Applied Ergonomics*, vol. 31, no. 2, pp. 201-205, 2000.

[20] S. Hart, "NASA Task Load Index (TLX). Volume 1.0; Paper and pencil package", NASA Ames Research Center, Moffett Field, CA United States, 1986.

[21] R. Patel and B. Davidson, *Forskningsmetodikens grunder*. Lund: Studentlitteratur, 2011.

[22] A. Bryman and E. Bell, *Business research methods*. Oxford: Oxford University Press, 2007.

[23] Marsden, "Credibility, validity, reliability and transferability", *Slideshare.net*, 2017.[Online].Available:https://www.slideshare.net/MarsdenTherapy/credibility-validity-reliability-and-transferability?next_slideshow=1. [Accessed: 01- May- 2017].

[24] Y. He and S. Dai, "Detecting the corners of light shape of automotive low-beam headlamp by inverse hough transform", in *2009 International Conference on Industrial and Information Systems*, Haikou, China, 2009.

[25] R. Collins, *Gradients and Edge Detection*, 1st ed. Penn State: Robert Collins, 2013, pp. 1-7.

[26] "Edge Detection on Live Video Stream - MATLAB & Simulink Example - MathWorks United Kingdom", *Se.mathworks.com*, 2017. [Online]. Available: https://se.mathworks.com/help/imaq/examples/edge-detection-on-live-video-stream.html. [Accessed: 29- May- 2017].

[27] K. Peterson and J. Lones, "Practical measure of headlamp beam alignment in vehicle assembly", in *Current Developments in Lens Design and Optical Engineering VII*, 2006.

[28] Headlamp Aiming & Testing System LUMINOSCOPE PLA 25. (2017). [ebook] Available:http://www.frenteknik.com/images/File/brosurler/Broch_PLA25_Eng.pdf [Accessed 8 Apr. 2017].

[29]"Bosch Automotive Aftermarket - Bosch Headlight Tester", *Headlighttester.com*,2017.[Online].Available:http://www.headlighttester.com/en/bosch-automotive-aftermarket. [Accessed: 29- May- 2017].

[30] S. Mattsson, Å. Fast-Berglund and D. Li, "Evaluation of Guidelines for Assembly Instructions", *IFAC-PapersOnLine*, vol. 49, no. 12, pp. 209-214, 2016.

[31] M. Alkahtani, H. Kaid, E. Nasr and M. Noman, "Six Sigma DMAIC phases application in Y company: a case study", *International Journal of Collaborative Enterprise*, vol. 5, no. 34, p. 181, 2016.

[32] Bratt, L. (2009). The Brundtland link between poverty and environmental degradation, and other questionable opinions. *International Journal of Innovation and Sustainable Development*, 4(1), p.74.

Appendices

Appendix A – Project Charter

GENERAL PROJECT INFORMATION

Project Name: Optimization of Manual Headlight Aiming Process at Volvo Cars Corporation

Project Sponsor: Thomas Johansson

Project Manager: Thomas Johansson

Organizational Unit: Volvo Cars Corporation Exterior System & Hatches, Torslanda

Process Impacted: Manual Headlight Adjustment

Expected Start Date: 2017/03/06
Expected Completion Date: 2017/07/23

Expected Gains: Reduced rework of headlight adjustment, Accurate results leads to providing reliable input for main line headlight aiming equipment.

Estimated Costs: Will be notified after the completion of Analysis phase

PROBLEM, ISSUE, GOALS, OBJECTIVES, DELIVERABLES

Problem or Issue: The manual headlight aiming process is totally dependent on operator judgement. Experts believe that data from this process is not reliable and hence cannot be used as input for further calibration of headlight aiming equipment at main line.

Purpose of Project: The purpose is to evaluate the existing procedure and look for quality improvements to obtain more reliable results from the process.

Expected Deliverables:

Preliminary Plan	Target Date	Actual Date
Define	2017/03/24	2017/03/24
Measure	2017/03/24	2017/03/31
Analyze	2017/05/19	2017/05/19
Improve	2017/06/09	2017/06/09
Control	2017/06/16	2017/06/16
Completion Date	2017/07/23	2017/06/26

PROJECT SCOPE & SCHEDULE

Within Scope: Manual Headlight Aiming Process

Outside of Scope: The headlight aiming equipment in main production line will not be evaluated in the study.

PROJECT RESOURCES

Project Team: Sujith Govindaraju & Yashwanth Prasad

Support Resources: VCC & Chalmers University of Technology

Special Needs: Technical Expertise within automobile pertaining to optics, electronics, electrical and safety.

PROJECTS BENEFITS & CUSTOMERS

Process Owner: Thomas Johansson

Key Stakeholders: VCC & Chalmers University of Technology

Final Customers: VCC

Expected Benefits: Reliable Results, No Rework

PROJECT RISKS, CONSTRAINTS

Risks: Availability of the literature concerning the area of study might impact the project outcome

Constraints: Availability of key stakeholders and expertise personnel timely to receive input

Appendix B – Process Inspection and Instruction (PII)

Type		No			Operation Description		Variant		
H		10			Drive car to dark room.				
I		20			Check that wheels are in correct position and that both tyres touches the front surface of the floor beam.				
I		25			Make sure that the gear lever is in NEUTRAL position and that the parking brake has NOT been activated.				
M		30			Apply laser to front windscreen using the correct gauge to position the laser in Y0. Start up the laser.				
K		35			Control that the Y0-Laser beam is within the marked area for the centering template. (See pictures)				
M		40			Start the Z-positioning laser and adjust the laser so it hits the lowest part of the kink reflector. (See Picture)		* LED A * LED A2 * LED A3 * LED A4 * LED B * LED B2 * LED B3 * LED B4		
M		45			Start the Z-positioning laser and adjust the laser so it hits the bulbcenter. (See Picture)		* HALO A * HALO B		
					Position the centering template so that the Y0 laser beam is lining up vertically with the fixed vertical marking on the centering template by adjusting the template.				
					Position both of the vertical centering line forks according to specification. (See Note)				
					Raise/Lower the white wall so that the horizontal 0- Line, lines up with Z-laser beam.				
					Turn off the wind screen laser and remove it from car.				
					Turn off the Z-Laser.				
					Activate Low Beam by putting the car in ignitionmode and press the hazard switch 2 times. Close the doors of the vehicle after the factory mode has been enabled.				

					Cover right headlamp.				
M		140			Measure the distance between the cut-off line and the horizontal 0-line at 300mm left from the breakpoint of the cut-off line according to specification.				
M		150			Measure the distance between the breakpoint of the cut-off line and the vertical centerline.				
					Document horizontal & vertical measurements in the control chart.				
					If deviation occurs, adjust headlights according to specification (See Notes). Remove US cap from adjustment screw and assemble it after adjustment.				
					FOR RIGHT SIDE				
					Cover Left headlamp.				
M		200			Measure the distance between the cut-off line and the horizontal 0-line at 300mm left from the breakpoint of the cut-off line according to specification.				
M		210			Measure the distance between the breakpoint (cut-off line & kink) and vertical centerline.				
					Document horizontal & vertical measurements in the control chart.				
					If deviation occurs, adjust headlights according to specification (See Notes). Remove US cap from adjustment screw and assemble it after adjustment.				

NOTES

TARGET VALUE HEIGHT: Z -8
TOLERANCES HEIGHT: Z -6,0 to -10,0
TARGET VALUE SIDE: Y 0
TOLERANCES SIDE: Y +8,0 to -8,0

IMPORTANT!!
IF LIGHTS ARE OUTSIDE THE GIVEN TOLERANCES; CALL RESPONIBLE INDUSTRIAL ENGINEER!

Type		No			Operation Description		Variant		
H		10			Drive car to dark room.				
I		20			Check that wheels are in correct position and that both tyres touches the front surface of the floor beam.				
I		25			Make sure that the gear lever is in NEUTRAL position and that the parking brake has NOT been activated.				
M		30			Apply laser to front windscreen using the correct gauge to position the laser in Y0. Start up the laser.				
K		35			Control that the Y0-Laser beam is within the marked area for the centering template. (See pictures)				
M		40			Start the Z-positioning laser and adjust the laser so it hits the lowest part of the kink reflector. (See Picture)		* LED A * LED A2 * LED A3 * LED A4 * LED B * LED B2 * LED B3 * LED B4		
M		45			Start the Z-positioning laser and adjust the laser so it hits the bulb center. (See Picture)		* HALO A * HALO B		
					Position the centering template so that the Y0 laser beam is lining up vertically with the fixed vertical marking on the centering template by adjusting the template.				
					Position both of the vertical centering line forks according to specification. (See Note)				
					Raise/Lower the white wall so that the horizontal 0-Line, lines up with Z-laser beam.				
					Turn off the wind screen laser and remove it from car.				
					Turn off the Z-Laser.				
					Activate Low Beam by putting the car in ignition mode and press the hazard switch 2 times. Close the doors of the vehicle after the factory mode has been enabled.				
					Open the Hood.				
					FOR LEFT SIDE				

*

					Cover right headlamp.				
M		140			Measure the distance between the cut-off line and the horizontal 0-line at the breakpoint of the cut-off line according to specification.				
M		150			Measure the distance between the breakpoint of the cut-off line and the vertical centerline.				
					Document horizontal & vertical measurements in the control chart.				
					If deviation occurs, adjust headlights according to specification (See Notes).				
					FOR RIGHT SIDE				
					Cover Left headlamp.				
M		200			Measure the distance between the breakpoint (cut-off line & kink) and vertical centerline.				
M		210			Measure the distance between the cut-off line and the horizontal 0-line at the breakpoint of the cut-off line according to specification.				
					Document horizontal & vertical measurements in the control chart.				
					If deviation occurs, adjust headlights according to specification (See Notes).				

*

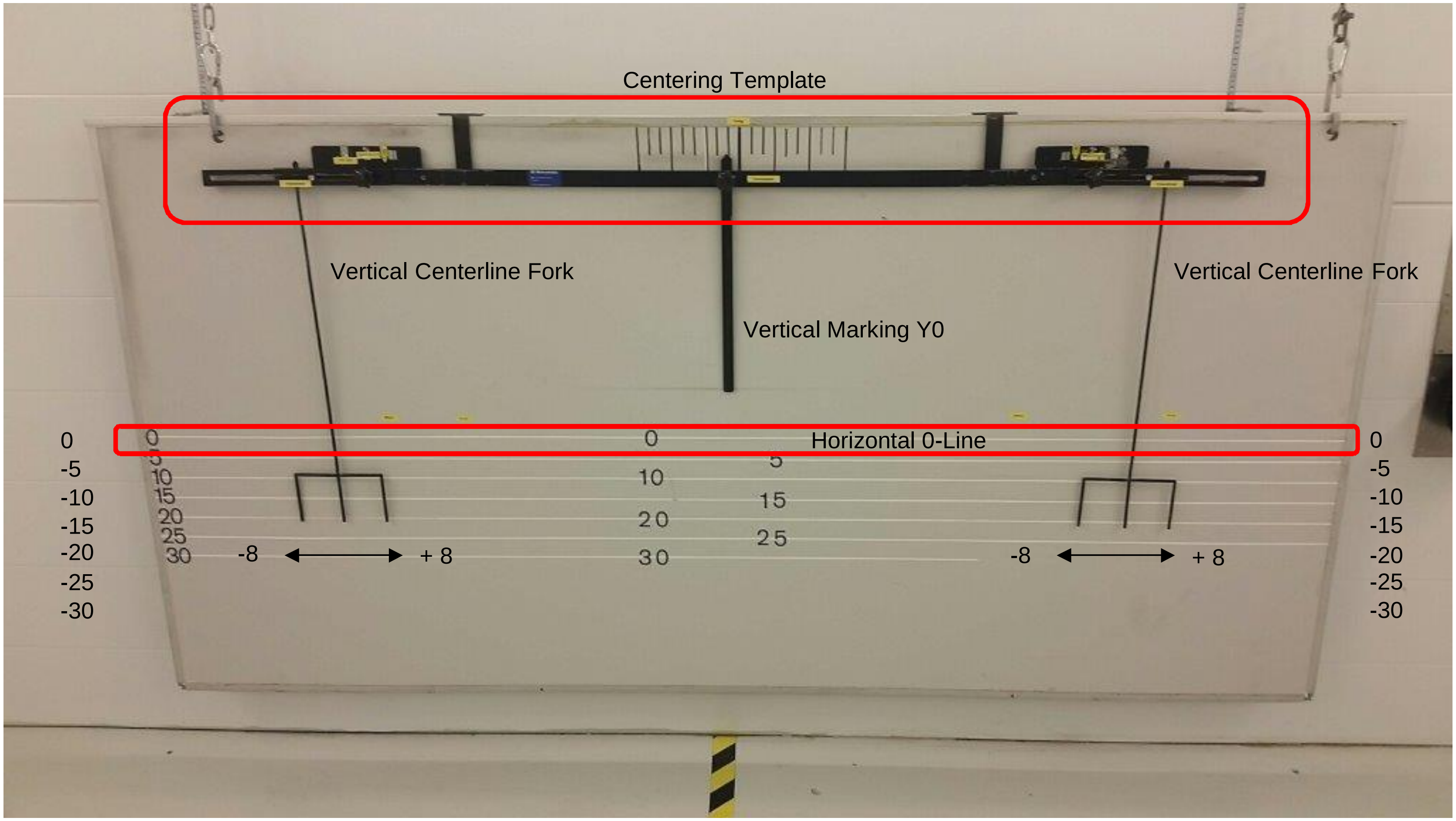
NOTES

EUROPE TARGETS
TARGET VALUE HEIGHT: Z -10
TOLERANCES HEIGHT: Z -8,0 to -
13,0 TARGET VALUE SIDE: Y 0
TOLERANCES SIDE: Y +10,0 to -10,0

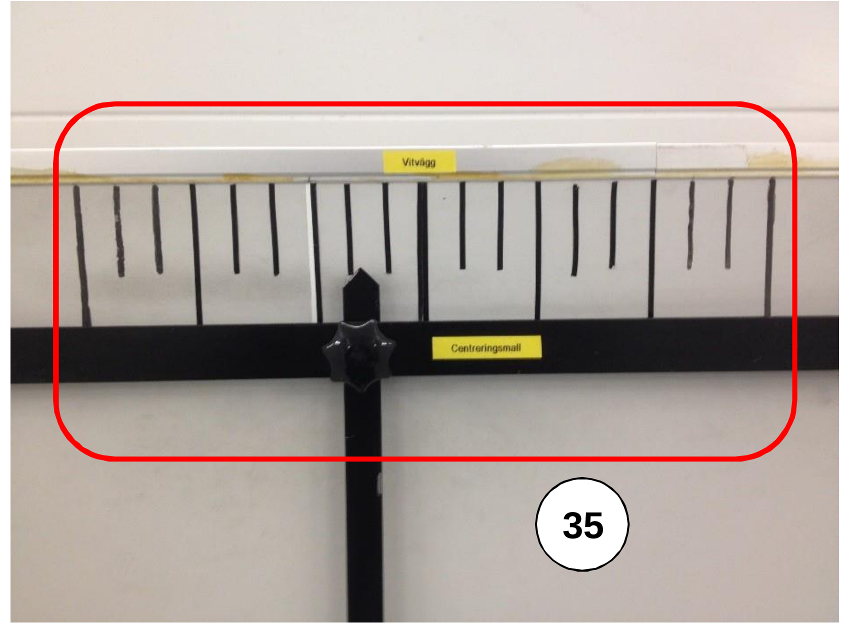
CHINA TARGETS
TARGET VALUE HEIGHT: Z -12
TOLERANCES HEIGHT: Z -10,0 to -
15,0 TARGET VALUE SIDE: Y 0
TOLERANCES SIDE: Y +10,0 to -10,0

IMPORTANT!!
IF LIGHTS ARE OUTSIDE THE GIVEN TOLERANCES; CALL RESPONIBLE INDUSTRIAL ENGINEER!

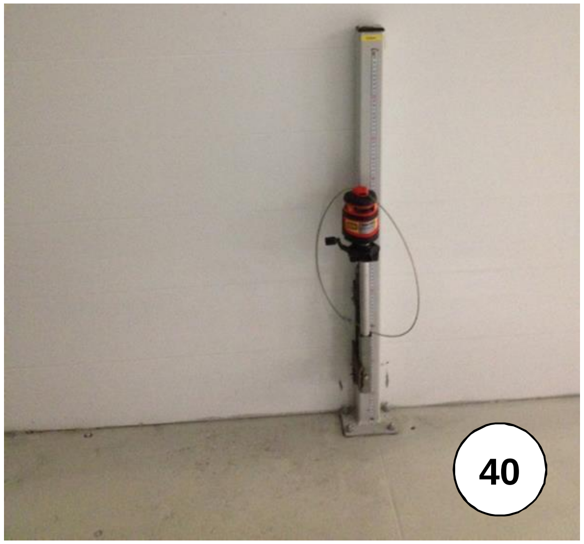
Darkroom Template




30


Vitvägg
Centreringsmall
35


50
0
5
10
15
20
25
30
0
10
20
30
5
15
25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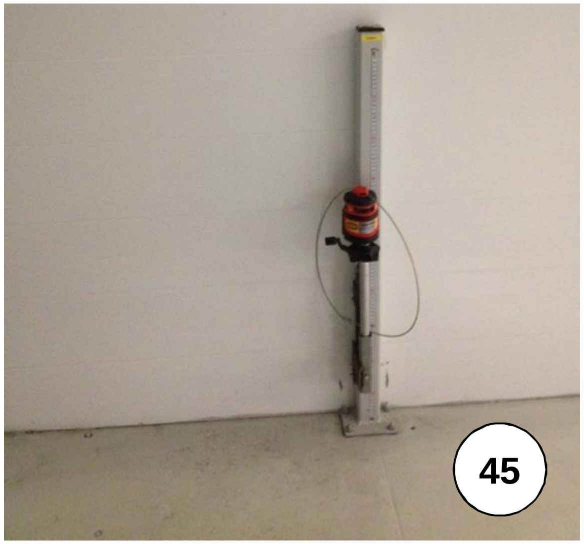
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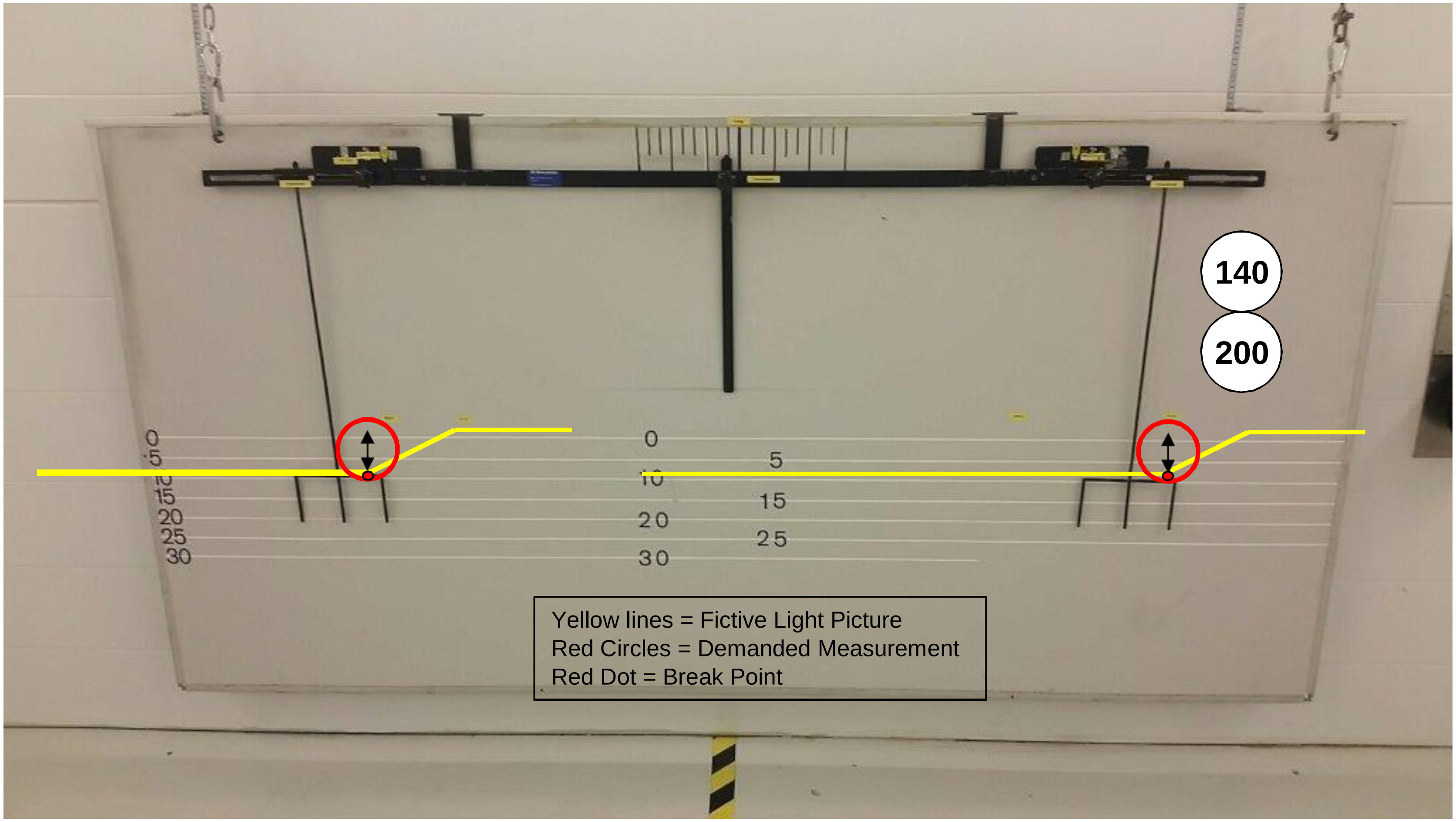
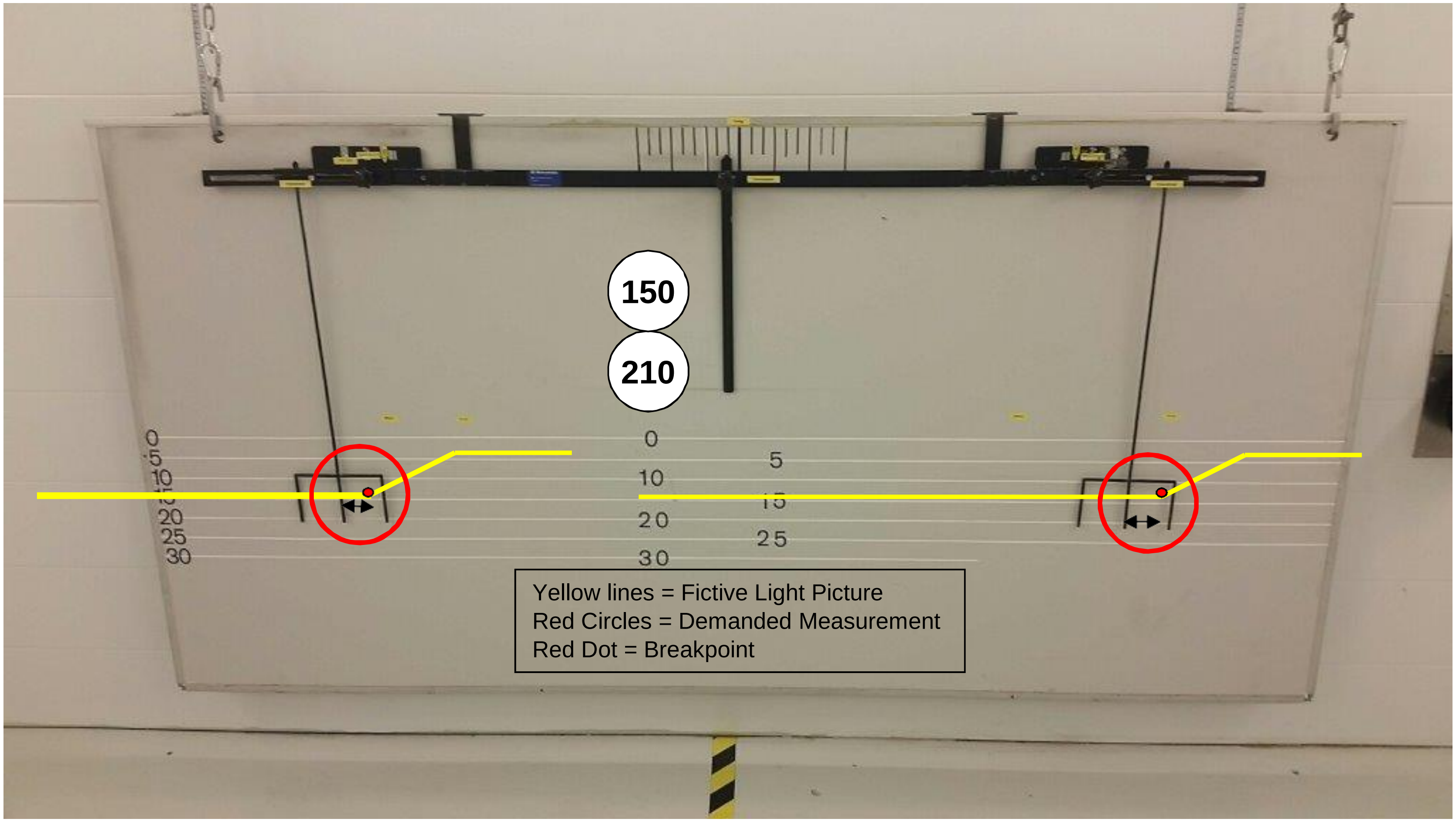
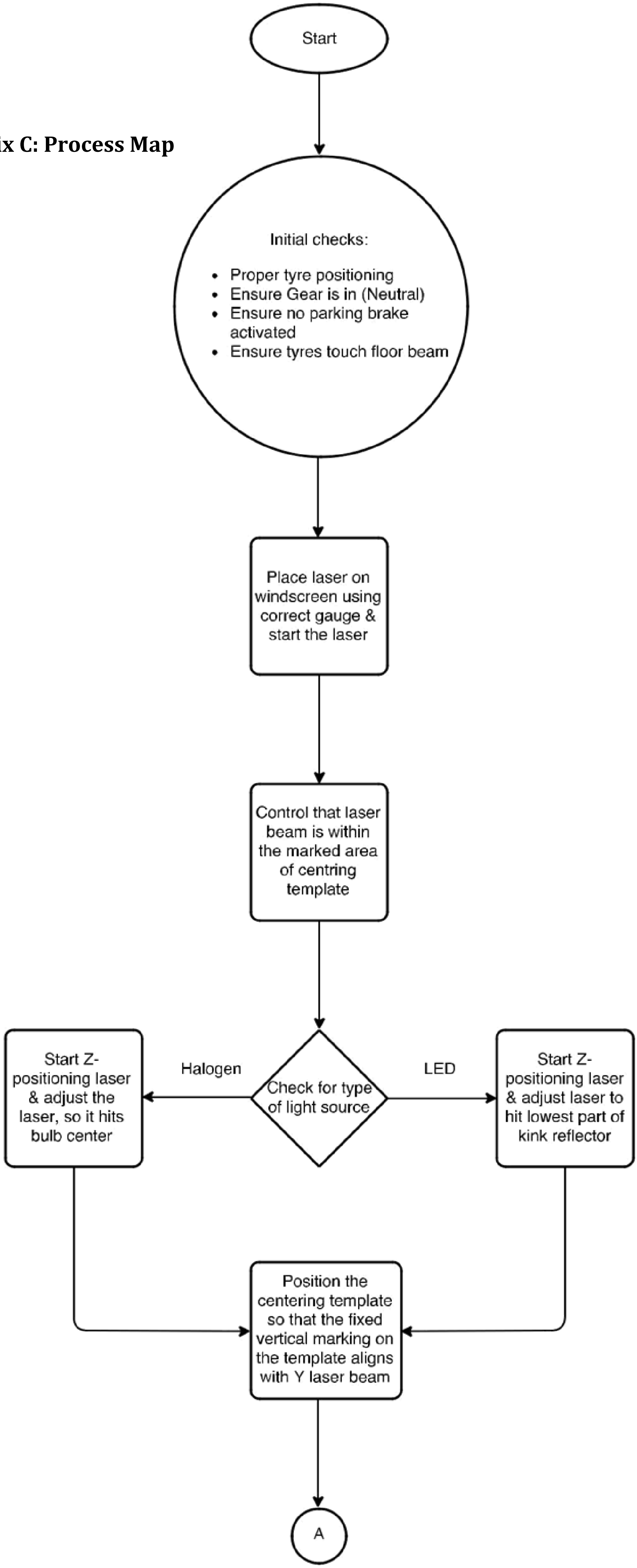
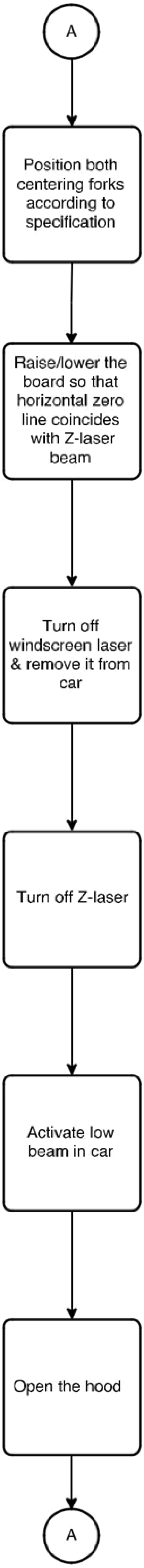


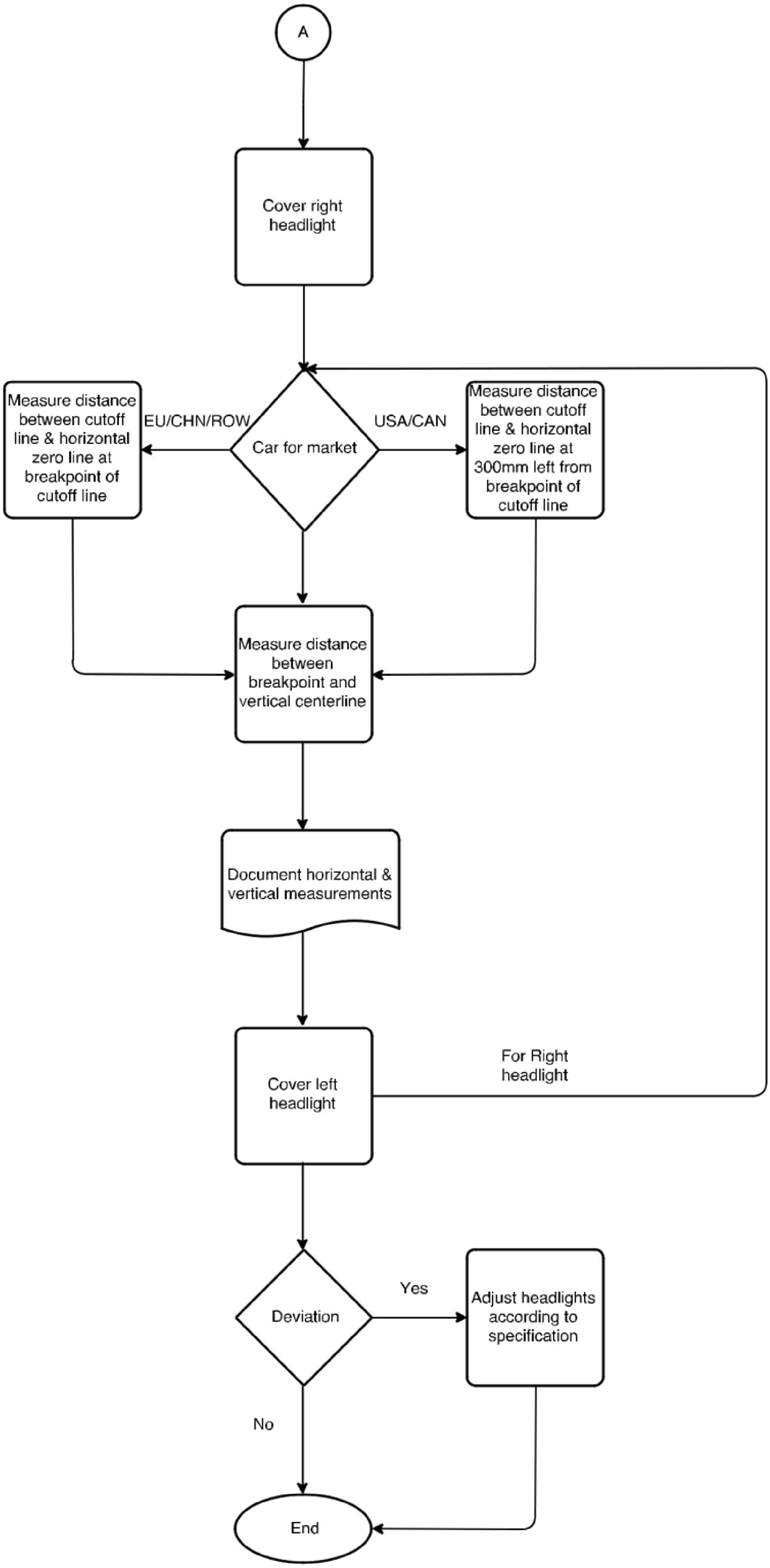
140
200
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Yellow lines = Fictive Light Picture
Red Circles = Demanded Measurement
Red Dot = Break Point


150
210
0
5
10
15
20
25
30
Yellow lines = Fictive Light Picture
Red Circles = Demanded Measurement
Red Dot = Breakpoint

Appendix C: Process Map




A
Position both centering forks according to specification
Raise/lower the board so that horizontal zero line coincides with Z-laser beam
Turn off windscreen laser & remove it from car
Turn off Z-laser
Activate low beam in car
Open the hood
A



A
Cover right headlight
Car for market
EU/CHN/ROW
USA/CAN
Measure distance between cutoff line & horizontal zero line at breakpoint of cutoff line
Measure distance between cutoff line & horizontal zero line at 300mm left from breakpoint of cutoff line
Measure distance between breakpoint and vertical centerline
Document horizontal & vertical measurements
Cover left headlight
For Right headlight
Deviation
Yes
Adjust headlights according to specification
No
End

Appendix D: Appraiser Variation Data Collection

			Yashwanth	Appraiser 1		
Trial No	Variant	Market	Left Headlight	Left Headlight	Right Headlight	Right Headlight
			Height (cm)	Side (cm)	Height (cm)	Side (cm)
1	V90	EU	-10	5	-8	5
2	V90	USA	-8	3	-10	2
3	V90	USA	-4	13	-5	11
4	S90	EU	-10	9	-9	7
5	XC90	USA	-6	2	-6	6
6	XC90	UK	-9	-8	-6	-3
7	V90	EU	-4	5	-9	5
8	V90	EU	-9	6	-8	5
9	V90	USA	-7	0	-9	1
10	XC90	USA	-10	4	-9	6
11	V90	USA	-9	4	-8	11
12	XC90	USA	-7	6	-9	11
13	XC90	USA	-9	0	-7	8
14	V90	EU	-10	8	-11	9
15	XC90	USA	-9	1	-9	0
16	XC90	USA	-9	5	-7	9
17	V90	EU	-7	6	-6	18
18	XC90	USA	-10	1	-10	4
19	XC90	USA	-9	6	-7	4
20	XC90	EU	-12	8	-9	10
21	XC90	USA	-6	2	-6	4
22	V90cc	EU	-4	7	-5	6
23	V90cc	EU	-4	10	-8	8
24	V90cc	EU	-6	10	-10	8
25	S90	EU	-7	9	-8	5
26	XC90	USA	-8	1	-7	0
27	XC90	USA	-8	7	-8	8
28	S90	EU	-10	7	-10	8
29	V90cc	EU	-4	6	-4	10
30	S90	JPN	-5	-8	-6	-10
31	V90	EU	-9	7	-5	5
32	V90	EU	-11	8	-10	8
33	V90cc	EU	-4	13	-4	12
34	V90cc	EU	-4	0	-4	11
35	V90	UK	-8	-8	-5	-6

			Sujith	Appraiser 2		
Trial No	Variant	Market	Left Headlight	Left Headlight	Right Headlight	Right Headlight
			Height (cm)	Side (cm)	Height (cm)	Side (cm)
1	V90	EU	-11	6	-11	4
2	V90	USA	-9	4	-9	2
3	V90	USA	-8	15	-10	10
4	S90	EU	-13	10	-14	6
5	XC90	USA	-10	1	-11	4
6	XC90	UK	-6	-4	-8	-4
7	V90	EU	-10	2	-11	2
8	V90	EU	-11	6	-10	5
9	V90	USA	-13	-2	-11	0
10	XC90	USA	-8	-2	-9	6
11	V90	USA	-12	3	-10	8
12	XC90	USA	-12	8	-11	12
13	XC90	USA	-12	2	-10	10
14	V90	EU	-12	10	-13	9
15	XC90	USA	-11	2	-10	1
16	XC90	USA	-11	4	-10	8
17	V90	EU	-10	9	-6	22
18	XC90	USA	-12	0	-11	2
19	XC90	USA	-10	6	-10	6
20	XC90	EU	-12	10	-8	8
21	XC90	USA	-9	2	-7	6
22	V90cc	EU	-7	6	-11	8
23	V90cc	EU	-10	8	-12	8
24	V90cc	EU	-12	10	-15	8
25	S90	EU	-11	8	-13	8
26	XC90	USA	-10	6	-9	0
27	XC90	USA	-10	7	-9	8
28	S90	EU	-15	0	-12	10
29	V90cc	EU	-8	2	-7	8
30	S90	JPN	-7	-7	-7	-8
31	V90	EU	-10	8	-10	7
32	V90	EU	-12	6	-13	6
33	V90cc	EU	-6	12	-10	10
34	V90cc	EU	-9	2	-7	10
35	V90	UK	-10	-4	-6	-8

			Volvo Operator	Appraiser 3		
Trial No	Variant	Market	Left Headlight	Left Headlight	Right Headlight	Right Headlight
			Height (cm)	Side (cm)	Height (cm)	Side (cm)
1	V90	EU	-10	7	-9	6
2	V90	USA	-9	7	-10	7
3	V90	USA	-5	15	-5	12
4	S90	EU	-11	8	-11	8
5	XC90	USA	-7	3	-7	7
6	XC90	UK	-10	-3	-10	-3
7	V90	EU	-5	4	-10	5
8	V90	EU	-10	6	-10	7
9	V90	USA	-8	0	-10	1
10	XC90	USA	-9	4	-9	5
11	V90	USA	-10	4	-9	11
12	XC90	USA	-8	7	-9	12
13	XC90	USA	-10	1	-8	7
14	V90	EU	-10	8	-12	12
15	XC90	USA	-10	1	-9	1
16	XC90	USA	-9	6	-8	8
17	V90	EU	-8	8	-6	20
18	XC90	USA	-11	0	-10	6
19	XC90	USA	-10	5	-8	9
20	XC90	EU	-10	8	-10	7
21	XC90	USA	-8	0	-7	5
22	V90cc	EU	-5	5	-6	8
23	V90cc	EU	-8	7	-10	8
24	V90cc	EU	-10	9	-11	8
25	S90	EU	-9	7	-10	7
26	XC90	USA	-8	2	-7	0
27	XC90	USA	-9	8	-8	9
28	S90	EU	-10	4	-10	7
29	V90cc	EU	-5	4	-6	8
30	S90	JPN	-5	-8	-9	-10
31	V90	EU	-10	8	-8	6
32	V90	EU	-10	8	-11	8
33	V90cc	EU	-5	15	-5	12
34	V90cc	EU	-5	0	-5	12
35	V90	UK	-8	-8	-5	-6

Appendix E: Interview Guide

Interview

Please note that the authors also came up with certain spontaneous questions or modified the listed questions accordingly during the actual interview. However, the base remains the same as the original question. Moreover, in the result section of the report the authors have project only the answers that was useful considering the scope of the thesis. Several answers were of detailed technical aspect of headlight and safety. Hence the answers are trimmed but credible as the authors never tried to form any kind of opinion.

Questioned addressed to R&D expert at VCC:

1. Share us your thoughts on what tools/methods could be used to improve the existing headlight aiming process of darkroom?

2. General Questions on the process, headlights and darkroom procedure.
    a. What are the different types of light sources used in headlights of various models of VCC cars? Briefly let us know the specifications details of different light sources?

    b. What are the factors considered for deciding beam patterns for headlights? Is it dependent on headlight designs or different country specifications?

    c. What is your opinion on the darkroom setup and procedure in the current state? Do you think it should be carried out within closed environment or open as it is in the current state?

    d. What according to you is the reason for unreliable results from the existing headlight aiming process?

Questions addressed to Tooling expert at VCC:

1. Can you briefly describe about the previous trials at darkroom, the setup of trial and assessment procedure?

2. General questions on Darkroom, headlight pattern, trials and their assessment.
    a. Can you give some insight on the previous experimental trial at darkroom and what caused its removal?
    b. Can you tell us briefly about how the assessment was carried out in the experimental trial phase?

3. Share with us your insights on what possible improvements could be realized in future towards improving the quality of headlight aiming process?

4. Can you share with us your insights on what areas could be explored towards finding solutions for improvement of the existing dark room process of headlight aiming?

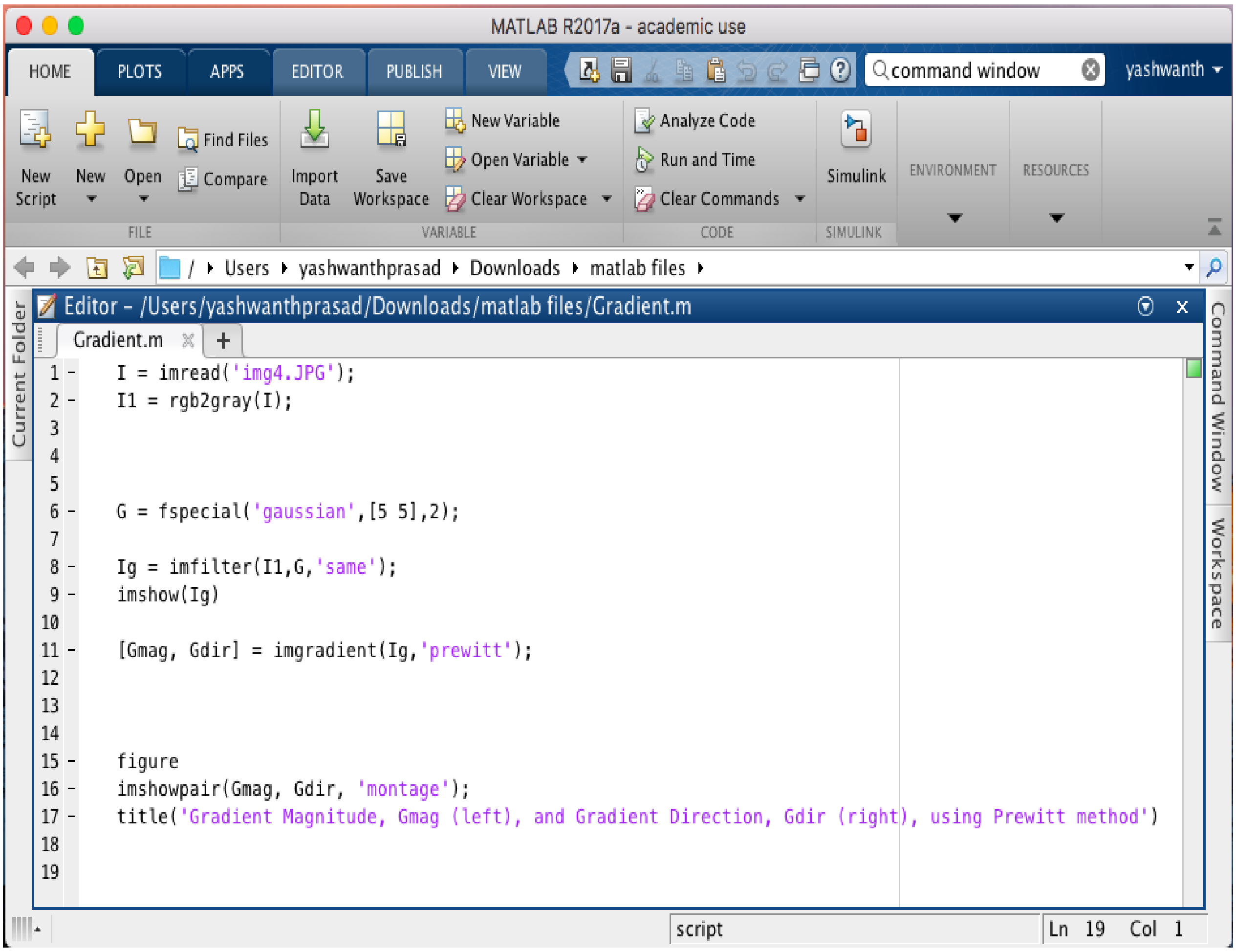
Questions addressed to Active safety expert at VCC:

1. Can you briefly give us an overview on the headlight safety requirements and demands?

2. Can you briefly explain on what could be the possible factors that affects the headlight from earning a good rating and what tests are carried out at VCC to ensure headlight meet the standards?

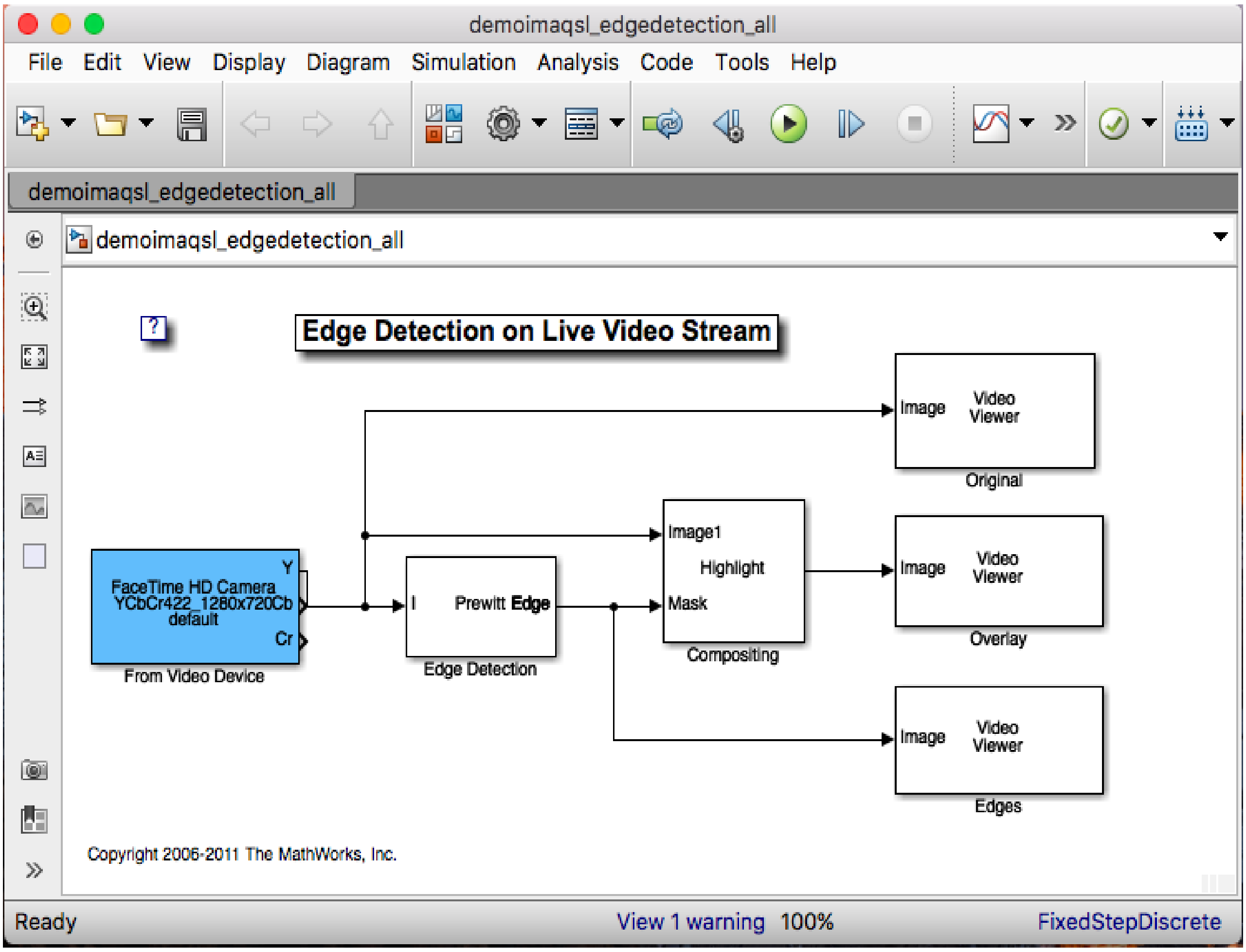
3. According to you what areas should be explored on towards looking for solutions to improve the darkroom headlight aiming process?

Appendix F: Algorithm used for Gradient Method




```
I = imread('img.JPG');
/* read an image into workspace */

I1 = rgb2gray(I);
/* read an image into workspace*/

G = fspecial('gaussian',[5 5],2);
/* apply gaussian filter */
//generally the numbers depend on the image captured//

Ig = imfilter(I1,G,'same');
/* reduce the image noise using gaussian filter */

imshow(Ig)
/* display the image */

[Gmag, Gdir] = imgradient(Ig,'prewitt');
/* calculate the gradient magnitude and direction using the directional gradients*/

figure
imshowpair(Gmag, Gdir, 'montage');
title('Gradient Magnitude, Gmag (left), and Gradient Direction, Gdir (right), using
Prewitt method')
/* display the gradient magnitude and direction in the image */
```

Appendix G: Simulink® Block for Edge Detection using Live Video Stream [26]



Appendix H: Assigned Physical and Cognitive Levels for Tasks in Current State

No	Tasks	Physical	Cognitive
1	**Initial Check**		
1.1	**Car**		
1.1.1	Ensure no parking brake activated	1	1
1.1.2	Ensure gear is neutral	1	1
1.1.3	Ensure wheels in straight position	1	1
1.1.4	Ensure tyre touch floor beam	1	1
2	**Alignment**		
2.1	**Y Positioning Laser**		
2.1.1	Place laser on windscreen using correct gauge	2	1
2.1.2	Switch on laser	1	1
2.1.3	Control the laser is within the marked area of centring template	1	1
2.2	**Z Positioning Laser**		
2.2.1	Switch on Laser	1	1
2.2.2	Adjust laser beam to lowest part of kink reflector/bulb centre	1	1
2.3	**Board**		
2.3.1	Align fixed vertical marking on centring template to Y laser beam	1	1
2.3.2	Position centring forks	1	1
2.3.3	Raise/Lower board Ensure horizontal zero line coincides Z laser beam	1	1
3	**Setting**		
3.1	**Laser**		
3.1.1	Turn of Y positioning laser & remove it from car	1	1
3.1.2	Turn off Z positioning laser	1	1
3.2	**Car**		

3.2.1	Activate Low Beam	1	1
3.2.2	Open Hood	1	1
4	**Measurement & Adjustment**		
4.1	**Headlamp**		
4.1.1	Cover Right Headlamp	1	1
4.1.2	Measure & Document	1	1
4.1.3	Adjust if necessary	2	1
4.1.4	Cover Left Headlamp	1	1
4.1.5	Measure & Document	1	1
4.1.6	Adjust if necessary	2	1

Appendix I: REBA Analysis

ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: **Board Adjustment** Date: **2017/04/07**

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 (10-20°) **+2** (20°+) +2 (in extension)

Neck Score: +2

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 (0°) +2 (in extension) +2 (0-20°) **+3** (20-60°) +4 (60°+)

Trunk Score: +3

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 3: Legs

+1 +2 Adjust: Add +1 (30-60°) Add +2 (>60)

Leg Score: +1

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 4

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 1

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A: 5

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck 1				Neck 2				Neck 3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B		Lower Arm 1			Lower Arm 2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C	Score B											
Score A	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 4 + Activity Score: 2 = REBA Score: 6

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 (20°, 20°) +2 (in extension, 20°) +2 (20-45°) +3 (45-90°) +4 (90°-)

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: +1

Step 8: Locate Lower Arm Position:

+1 (60-100°) +2 (100°+, 0-60°)

Lower Arm Score: +1

Step 9: Locate Wrist Position:

+1 (15°, 15°) +2 (15°+, 15°+)

Wrist Score: +1

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B: 1

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score: 0

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B: 1

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

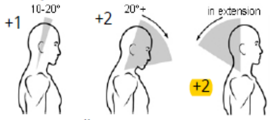
ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: **Fork Adjustment** Date: **2017/04/07**

A. Neck, Trunk and Leg Analysis

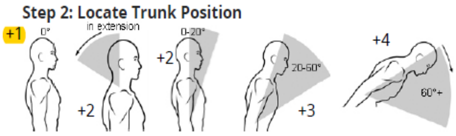
Step 1: Locate Neck Position



+2
Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

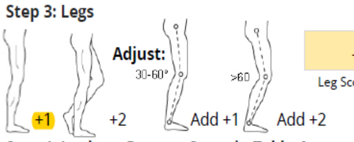
Step 2: Locate Trunk Position



Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

+1
Trunk Score

Step 3: Legs



+1
Leg Score

Step 4: Look-up Posture Score in Table A

Using values from steps 1-3 above,
Locate score in Table A

1
Posture Score A

+

Step 5: Add Force/Load Score

If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

0
Force / Load Score

=

Step 6: Score A, Find Row in Table C

Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C.**

1
Score A

Scoring

1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck											
		1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

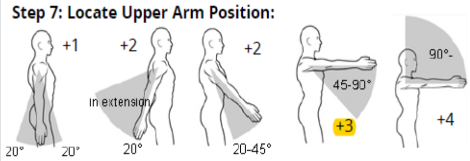
Table B		Lower Arm					
		1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Score A	Table C											
	Score B											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

3 + 0 = 3
Table C Score | Activity Score | REBA Score

B. Arm and Wrist Analysis

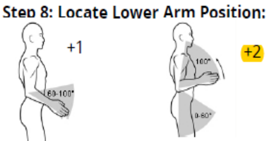
Step 7: Locate Upper Arm Position:



Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

+4
Upper Arm Score

Step 8: Locate Lower Arm Position:



+2
Lower Arm Score

Step 9: Locate Wrist Position:

+2
Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B

Using values from steps 7-9 above, locate score in Table B

6
Posture Score B

+

Step 11: Add Coupling Score

Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

0
Coupling Score

=

Step 12: Score B, Find Column in Table C

Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

6
Score B

Step 13: Activity Score

+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: **Horizontal Laser Alignment** Date: **2017/04/07**

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 (10-20°) +2 (20°+) in extension **+2**

Neck Score: +2

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 (0°) in extension +2; +2 (0-20°); 20-60° **+3**; +4 (60°+)

Trunk Score: +3

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 3: Legs

+1 **+2** Adjust: 30-60° Add +1; >60 Add **+2**

Leg Score: +4

Step 4: Look-up Posture Score in Table A

Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 7

Step 5: Add Force/Load Score

If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 0

Step 6: Score A, Find Row in Table C

Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A: 7

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A

Trunk Posture Score	Neck 1: Legs 1	2	3	4	Neck 2: Legs 1	2	3	4	Neck 3: Legs 1	2	3	4
1	1	2	3	4	1	2	3	4	3	3	5	6
2	2	3	4	5	3	4	5	6	4	5	6	7
3	2	4	5	6	4	5	6	7	5	6	7	8
4	3	5	6	7	5	6	7	8	6	7	8	9
5	4	6	7	8	6	7	8	9	7	8	9	9

Table B

Upper Arm Score	Lower Arm 1: Wrist 1	2	3	Lower Arm 2: Wrist 1	2	3
1	1	2	2	1	2	3
2	1	2	3	2	3	4
3	3	4	5	4	5	5
4	4	5	5	5	6	7
5	6	7	8	7	8	8
6	7	8	8	8	9	9

Table C

Score A	Score B 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 7 + Activity Score: 0 = REBA Score: 7

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 (20° 20°) +2 (in extension, 20°) **+2** (20-45°) +3 (45-90°) +4 (90°+)

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: +2

Step 8: Locate Lower Arm Position:

+1 (60-100°) +2 (100°+, 0-60°)

Lower Arm Score: +1

Step 9: Locate Wrist Position:

+1 (15°) +2 (15°+)

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add **+1**

Wrist Score: +2

Step 10: Look-up Posture Score in Table B

Using values from steps 7-9 above, locate score in Table B

Posture Score B: 2

Step 11: Add Coupling Score

Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score: 0

Step 12: Score B, Find Column in Table C

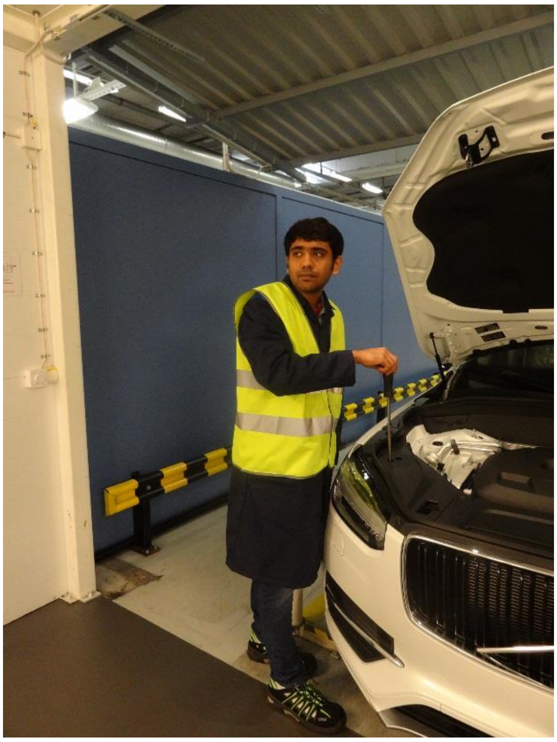
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B: 2

Step 13: Activity Score

+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205



ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: Headlight Adjustment   Date: 2017/04/07

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 (10-20°) +2 (20°+) +2 (in extension)

Neck Score: +2

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 (0°) +2 (in extension) +2 (0-20°) +3 (20-60°) +4 (60°+)

Trunk Score: +2

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 3: Legs

+1 +2 Adjust: Add +1 (30-60°) Add +2 (>60)

Leg Score: +1

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 3

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 0

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C.**

Score A: 3

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B	Lower Arm	1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C Score A	Score B 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 2 + Activity Score: 0 = REBA Score: 2

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 (20°, 20°) +2 (in extension, 20°) +2 (20-45°) +3 (45-90°) +4 (90°-)

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: +2

Step 8: Locate Lower Arm Position:

+1 (60-100°) +2 (100°, 0-60°)

Lower Arm Score: +1

Step 9: Locate Wrist Position:

+1 (15°, 15°) +2 (15°+, 15°+)

Wrist Score: +1

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B: 1

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score: 0

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B: 1

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: **Vertical Laser Alignment** Date:**2017/04/07**

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 (10-20°) +2 (20°+) +2 (in extension)

Neck Score: +2

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 (0°) +2 (in extension) +2 (0-20°) +3 (20-60°) +4 (60°+)

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score: +4

Step 3: Legs

+1 +2 Adjust: 30-60° Add +1; >60 Add +2

Leg Score: +2

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 6

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 0

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A: 6

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B	Lower Arm	1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C Score A	Score B 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 8 + Activity Score: 0 = REBA Score: 8

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 (20° / 20°) +2 (in extension, 20°) +2 (20-45°) +3 (45-90°) +4 (90°+)

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: +3

Step 8: Locate Lower Arm Position:

+1 (60-100°) +2 (100°+, 0-60°)

Lower Arm Score: +2

Step 9: Locate Wrist Position:

+1 (15° / 15°) +2 (15°+ / 15°+)

Wrist Score: +1

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B: 4

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score: 1

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B: 5

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix J: NASA TLX Rating by Operators

Operator 1 -

Operator 2 -


Rating Scales Summary
Mental Demand
Low
High
Physical Demand
Low
High
Temporal Demand
Low
High
Performance
Good
Poor
Effort
Low
High
Frustration
Low
High