Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Study of Application of Lean Six Sigma Methodology to Increase Efficiency of Processes in Production

Master's Final Degree Project

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Kaunas, 2025

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Industrial Engineering and Management (6211EX018)

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Task of the Master's Final Degree Project

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1. Title of the Project

Study of Application of Lean Six Sigma Methodology to Increase Efficiency of Processes in Production

(In English)

Lean 6 Sigma metodikos taikymo procesų efektyvumui gamyboje didinti tyrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to investigate the effectiveness of Lean Six Sigma methodology adaptation in production process for efficiency improvement.

Tasks:

1. to research Lean Six Sigma methodology application in manufacturing companies;
2. to analyze Lean Six Sigma application for process efficiency improvement in production processes;
3. to implement Lean Six Sigma and quality control tools for process efficiency improvements in electronic component production process;
4. to compare achieved efficiency results before and after Lean Six Sigma application;
5. to calculate economic benefits of Lean Six Sigma implementation.

3. Main Requirements and Conditions

Process performance data from a manufacturing company. Possibility of accessing manufacturing facility for further process analysis. Use of pareto chart, Value stream mapping, process flowchart, 5s, cause and effects diagram, process efficiency calculation, spaghetti diagram.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

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Žydrūnas Griškevičius. Study of Application of Lean Six Sigma Methodology to Increase Efficiency of Processes in Production. Master's Final Degree Project, supervisor assoc. prof. dr. Rūta Rimašauskienė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: lean; six sigma; efficiency; electronic product; production; process; DMAIC.

Kaunas, 2025. 63 p.

Summary

Lean Six Sigma is a methodology used for process cycle efficiency improvement and defect reduction by using quality control tools in conjunction with lean tools. During research, it was noticed that there were gaps for DMAIC applications for manufacturers who produce electronic devices and electronic component production processes. Therefore, LSS with the DMAIC has been used to analyze an electronic part manufacturing process in a smart water meter manufacturer. Furthermore, the structured analysis method has been proven to be beneficial as root causes of inefficient process cycle activities were found in the automated battery soldering operation. Suggestions to eliminate non-value-added activities were proposed as the root cause was found to be the defects generated from the soldering station needing rework, thus increasing the cycle time of the operation. Therefore, suggestions for process improvement were implemented by changing out the solder material, creating quality control procedures for new solder material batches, and improving warehousing conditions. Moreover, setup time has also been improved by eliminating walking time by introducing improvements in the workstation layout. After implementing suggestions, the process cycle efficiency has been improved by 5.26% as the daily output throughout 3 shifts improved by 21.28%, leading to 1659.85 EU monthly savings. In addition to financial benefit, the creation of standard operating procedures and 5S implementation were utilized to improve variation, uncertainty, and doubtfulness from the operators, thus providing social benefit. After analysis and improvements, it was shown that Lean Six Sigma can be utilized for electronic product manufacturers, not limited to being only used in textile, automotive parts, food, health providers, and service provider industries for production process cycle efficiency improvement.

Žydrūnas Griškevičius. Lean 6 Sigma metodikos taikymo procesų efektyvumui gamyboje didinti tyrimas. Magistro baigiamasis projektas, vadovė doc.dr. Rūta Rimašauskienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: lean; 6 Sigma; efektyvumas; elektronikos produktas; gamyba; procesas; DMAIK.

Kaunas, 2025. 63 p.

Santrauka

Lean 6 Sigma yra metodika kuri taikoma proceso ciklo efektyvumui didinti bei defektų mažinimui naudojant kokybės kontrolės bei Lean įrankius. Tyrimo metu pastebėta, kad gamintojams, kurie gamina eleketroninius prietaisus pasitelkiant elektroninių komponentų gamybos procesais, Lean 6 Sigma metodikos taikymas su DMAIK ciklu yra retas, kadangi publikacijų kiekis yra ribotas. Todėl Lean 6 Sigma analizės metodika su DMAIK struktūra buvo panaudota išmaniųjų vandens skaitiklių gamintojo elektroninių komponentų gamybos procese. Taikant struktūrine analizę buvo įrodytą, kad metodika yra naudinga, nes buvo nustatytos pagrindinės neefektyvios proceso ciklo veiklos priežastys automatizuotoje baterijų litavimo operacijoje. Buvo pateikti pasiūlymai pašalinti pridėtinės vertės nekuriančias veiklas, nes pagrindine rasta priežastis yra litavimo stotyje atsiradę defektai didinantys operacijos ciklo laiką. Todėl, buvo įgyvendinti siūlymai dėl proceso efektyvinimo, pakeičiant naudojamo lydmetalio gamintoją, sukuriant naujų litavimo medžiagų partijų kokybės kontrolės procedūras bei pagerinus sandeliavimo sąlygas. Taipogi, patobulinus darbo vietos išdėstymą, sumažintas vaikščiojimo laikas pasiimant komponentus. Įgyvendinus pasiūlymus, proceso ciklo efektyvumas pagerėjo 5,26%, kol visos dienos našumas per visas tris pamainas padidėjo 21,28%, dėl ko sutaupoma 1659,85 EU kas mėnesį. Be finansinės naudos siekemybės, standartinės veiklos procedūros sūkurimas ir 5S įdiegimas sumažino proceso variaciją, neapibrėžtumą bei abėjones, taip suteikiant socialinę naudą įmonėje. Atlikus analizę ir patobulinimas, buvo įrodyta, kad Lean 6 Sigma metodika gali būti panaudota elektronikos gaminių gamintojų procesuose, siekiant pagerinti gamybos proceso efektyvumą, neapsiribojant vien tik tekstilės, automobilių dalių, maisto, sveikatos priežiūros paslaugų bei paslaugų tiekėjų industrijomis.

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Introduction

New regulations and rising customer needs and requirements are pushing companies to optimize their production processes to keep them relevant in the industry. Quality control tools have been developed and used since the first Industrial Revolution. With the development of new technologies and rising quality standards, more quality control tools have been developed to combat the quality challenges in a manufacturing or service company. Moreover, Six Sigma methodology has been developed to decrease defects and improve process variability closer to the lowest variability. Lean tools have been developed and utilized in automotive manufacturing processes, but have lately been used in most production-as-a-service companies. Therefore, a new branch that is a combination of Lean tools and the Six Sigma DMAIC cycle has emerged, which is aimed at increasing the effectiveness of Six Sigma application by not only reducing defects but also decreasing process cycle time and improving the of information and materials throughout the production process. The current problem many companies are facing is the shutdown of Lean Six Sigma projects before they are fully implemented because of poor communication, improper project management, and top management negligence, as they do not fully understand the financial and sustainable benefits the improvements could bring. The introduction of Industry 4.0 technologies has introduced new opportunities to utilize these technologies for process improvements, as quality control tools could be used in conjunction with new emerging technologies to reduce the defect rate or improve process cycle efficiency. Every application of Lean Six Sigma is novel, as the outcome and the solutions for the outcome are not known until the analysis of the process is done. Therefore, LSS activities are usually identified as projects, as the definition of a project is an activity that is not standard, and the delivery has never been done before, as some of the procedures could be new and innovative. Although the usage of already known and tried methods, such as Six Sigma, has been researched to yield positive results for defect reduction financially, the sustainability factor is also considered, as the usage of quality control tools directly involves resource usage efficiency analysis and scrap reduction in manufacturing companies. In addition, simulation technology could greatly improve the effectiveness of Lean Six Sigma applications for production process efficiency improvements, as a well-structured simulated environment could be used for the analysis of the process and improvement implementation verification, which would bring new ideas, or better suggestions could be applied for the production process. In conclusion, quality control tool usage is essential to keep up with the rising demands from customers and the government for product quality, price, and quick delivery, therefore, LSS application with Industry 4.0 technology would bring positive benefits to the manufacturers, yielding higher profits.

Aim: to investigate the effectiveness of Lean Six Sigma methodology adaptation in the production process for efficiency improvement.

Tasks:

1. to research Lean Six Sigma methodology application in manufacturing companies;
2. to analyze Lean Six Sigma application for process efficiency improvement in production processes;
3. to implement Lean Six Sigma and quality control tools for process efficiency improvements in electronic component production process;
4. to compare achieved efficiency results before and after Lean Six Sigma application;
5. to calculate the economic benefits of Lean Six Sigma implementation.

Hypothesis: Lean Six Sigma methodology with DMAIC cycle application in electronic product manufacturing processes can improve process cycle efficiency by 5%.

1. Manufacturing Issues and Problem-Solving Techniques for Production Processes

The rising number of new technologies in manufacturing processes has created a need for quality control tools, which could be used for process efficiency and product quality improvements. There has been a change with industry 4.0 technology as customer expectations have shifted to a highly customizable product. Moreover, the shift to a highly customizable product has created challenges for the manufacturers, which affects the efficiency of the processes and defect generation. Therefore, quality control tools are used to alleviate the effects of rapid changes in production and process inefficiencies.

1.1. Efficiency and Quality Problems in Production Processes

The rise in customer requirements for a product has shifted to highly customizable products, where there is a high amount of variability in the product that is being manufactured. Therefore, manufacturing and assembly operations must be of a high flexibility and be able to achieve mass production costs [1]. Moreover, the current evaluation of production effectiveness does not consider the flexibility aspect of production. Furthermore, companies still need to use process improvement tools and key performance indicators to have efficient and effective improvements in the production line. Most production lines and manufacturers are using the most important key performance evaluation tool, which is Overall Equipment Effectiveness (OEE) [1]. OEE is used to indicate the losses and unused effort in a production line, indicating that the machines are not fully utilized. OEE is essential in process improvement techniques that need to be used for waste reduction and optimization of production to create a better flow. Highly customizable products have a high amount of changeover operations, which creates slower flow throughout production by various setup times and slower production cycles [1]. Furthermore, this negatively affects the OEE performance indicator of production, which is mostly meant for processes that do not have a high amount of flexibility, and therefore, creating a framework for operational measurement that combines productivity, and flexibility would be beneficial with the current manufacturing trends [1]. In conclusion, a new approach to process improvement in production is needed, to take into considerations that come from high production flexibility.

In most of the production companies, the effectiveness of process flow is usually underutilized, and the OEE does not reach the desired goal. Research done in the cement manufacturing industry indicated that while the benchmark for OEE is indicated to be at 85%, the industry average has been calculated to be at 65.60% [2]. Moreover, the effectiveness problems seem to be related to non-value-added activities, low productivity of machines, and inefficiency of labor. Furthermore, it was indicated that these problems came from the lack of knowledge and utilization of lean tools and lean philosophies. Evaluating that other industries have a rising need for customizable products, it is clear to acknowledge that the lack of Overall Equipment Effectiveness in all production processes is frequent, and there is a need to improve this effectiveness to stay competitive in the global market. In conclusion, there are inefficiencies currently in the manufacturing industry, which indicate that processes need to be improved by improvements done through various tools.

The need to be competitive in the market is that companies utilize quality control tools to improve the efficiency and quality of the product. The main quality control tools are divided into seven categories, which are histograms, cause and effect diagrams, check sheets, Pareto diagrams, flowcharts, control charts, and scatter diagrams [3]. Visual representation of the 7 basic quality control tools is shown in Fig. 1. The seven basic quality control tools are still used as they provide a holistic approach to problem-solving activities [4]. The application of quality control tools can be used for defect evaluation and reduction, and efficiency improvements in a manufacturing company [3]. Histograms are used for understanding quality control issues in production, while cause and effect diagrams, otherwise called fishbone diagrams, can potentially show the root cause of the variables that are causing the defects. The application of quality control tools in various production processes helps to improve production processes and product quality [4]. Moreover, the usage of quality control tools with Six Sigma process analysis can generate even more positive benefits, as structured planning for analysis and measurements can greatly impact the process improvement progress [4-6]. Furthermore, other quality control tools that were previously mentioned are used for the same reason, which is process analysis and improvement. In conclusion, product quality is important, and for the production process to be effective, quality control tools are essential to be utilized in a manufacturing company.

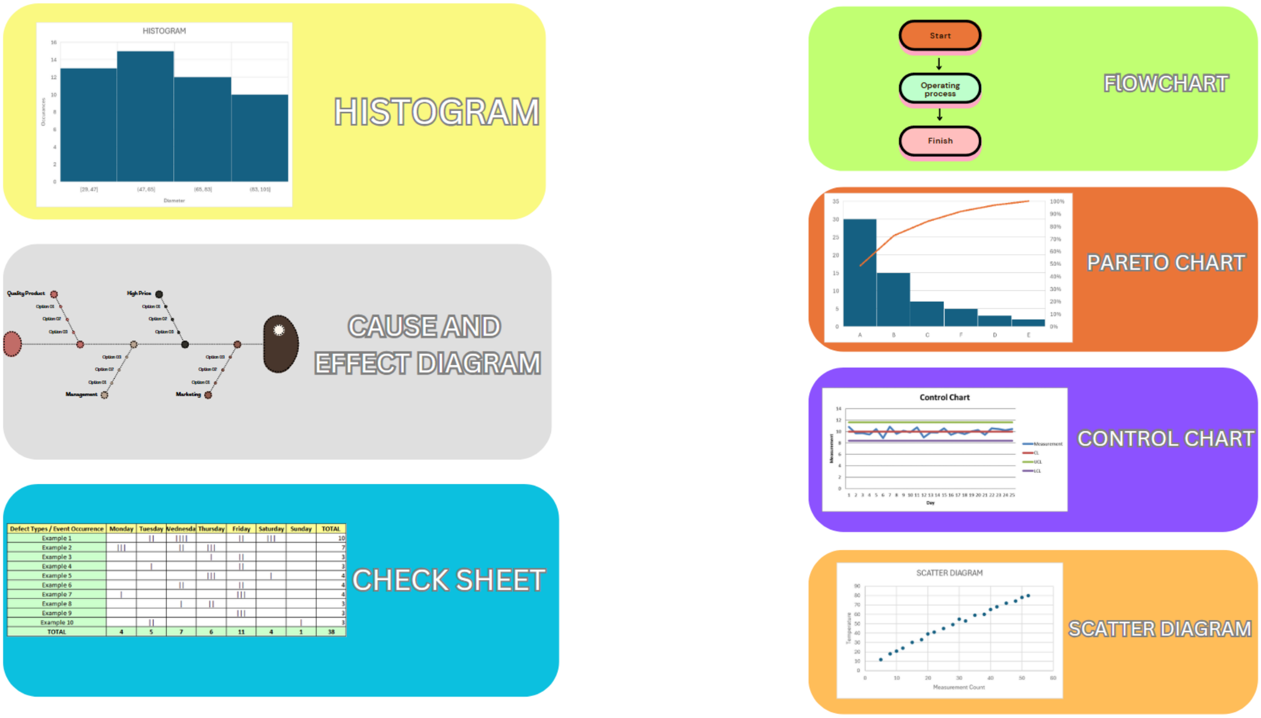

Fig. 1. 7 Basic Quality Control Tools

Six-sigma methodology is used to achieve the lowest number of defects for production while also decreasing variations. Six-sigma is a widely used quality control method, which helps eliminate bottlenecks and creates incentives to deliver a consistent result, which in this case would be the quality of the product [4]. Six-Sigma is used with a five-step approach, which is known as the DMAIC cycle. The DMAIC cycle consists of Define, Measure, Analyze, Improve, and Control stages, which can be seen in Fig. 2 [4]. The current situation in the very competitive product manufacturing industry is to sustain good performance for the long run [5]. Nevertheless, DMAIC cycle is a great tool for companies to sustain good performance for a long period as DMAIC is not only used for defect reduction but also improvement control in the last stage, which is mainly used to keep the suggested improvements in production line controlled, so they do not vary from theoretical solutions [4, 5]. Furthermore, Six-Sigma has several advantages for the companies while mainly being an economic advantage over competitors, as with the reduction of defects, creating a higher quality product, and increasing customer satisfaction, the benefits are the decrease in inputs in production and an increase in outputs to the customer.

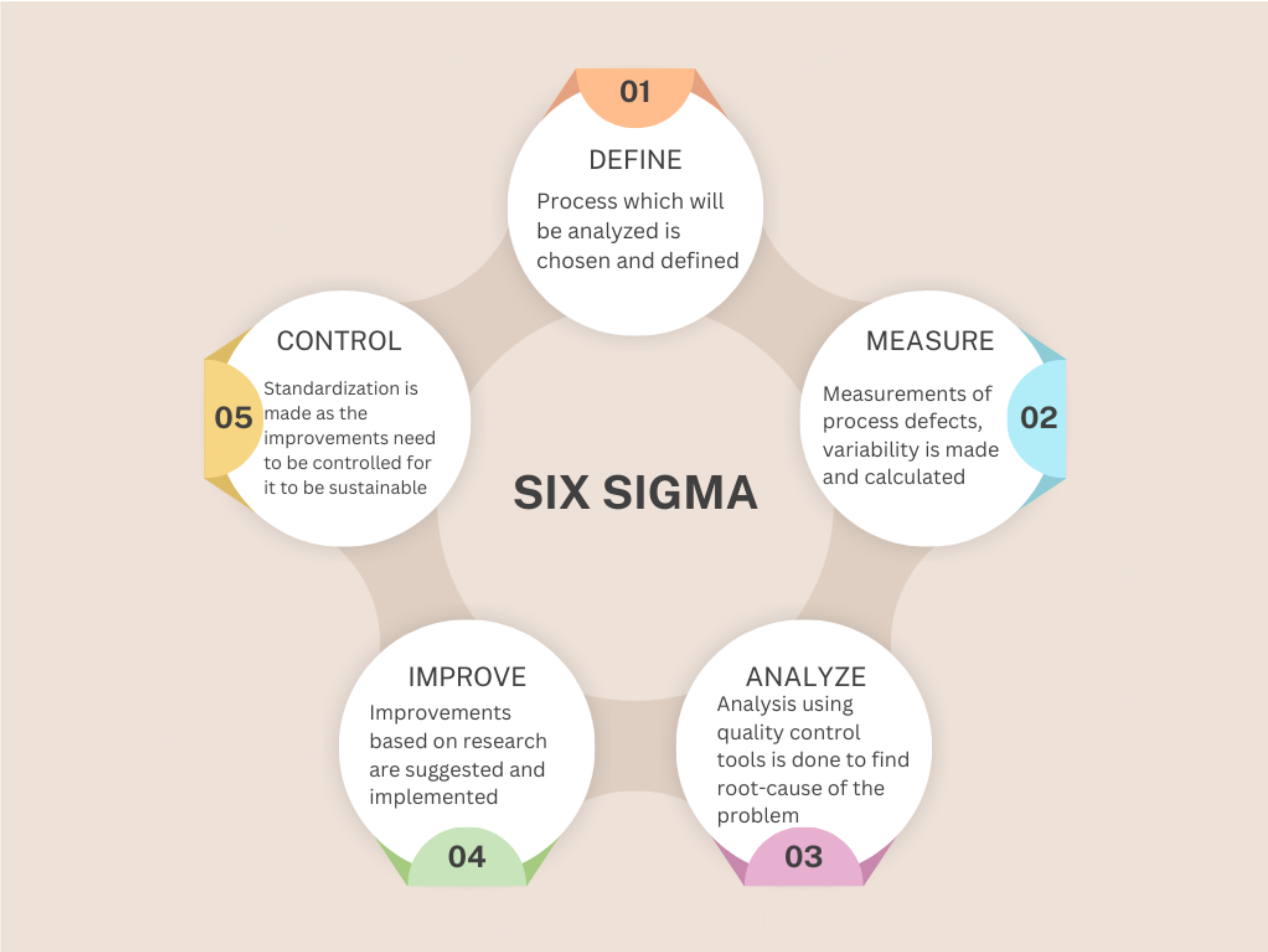

Fig. 2. DMAIC Cycle of Six Sigma

The economic benefits of Six Sigma can greatly outweigh the cost of the implementation. The Motorola company has spent around 170 million dollars on employee training, which has resulted in 2.2 billion in savings [4]. The improvements that were made by using DMAIC with the combination of quality control tools are substantial, which can be seen from [4-6]. That is why many businesses have implemented the Six Sigma methodology in their production analysis processes to improve their competitive standing with other companies [4-6]. Furthermore, the DMAIC cycle alone is not enough for employee training, as the usage of previously mentioned quality control tools, such as cause-and-effect diagrams, histograms, and Pareto charts, is essential to have positive results for the manufacturing company. Finally, while training employees with Six Sigma methodology might have a high initial cost, it also brings great financial benefit to the companies that implement these analysis and improvement methods in their processes.

Six Sigma's main goal is to achieve as close to zero defect manufacturing as possible. Moreover, theoretically, it should be possible to achieve 3.4 defects per million opportunities (DPMO) by implementing Six Sigma methodology in processes. Although in most cases the DPMO amount can only be reduced, no company has achieved the DPMO of 3.4 in processes of production [4-6]. While reduction is essential and a positive outcome, for some reason, the target has not been achieved, because while reduction of defects is essential, there might be a barrier where costs outweigh the benefit gained from implementing solutions and improvements suggested by DMAIC analysis. Furthermore, development in new technologies has outweighed the basic analysis of Six Sigma, and new methodologies have been introduced for further improvement of processes, such as Lean tools. Finally, while Six Sigma is still used for process defect and variation reduction, there will be a moment when the costs of implementing improvements will be higher than the benefits it brings.

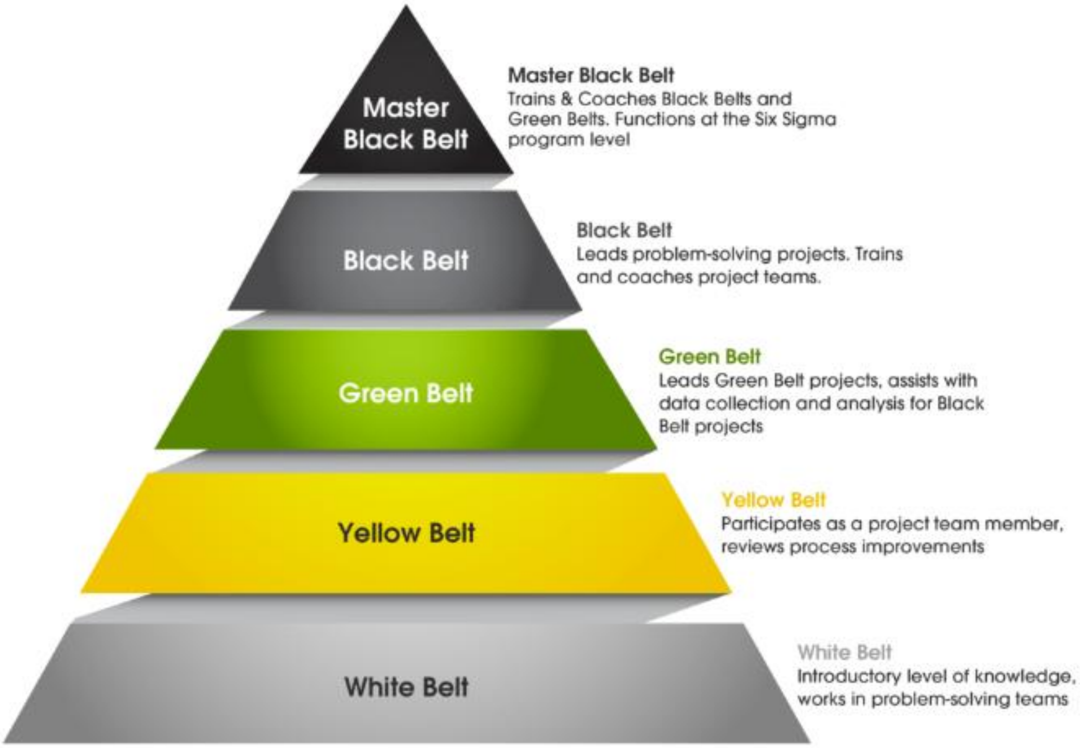

Fig. 3. Six Sigma and Lean Six Sigma Certification Levels [7]

To perform Six Sigma methodology on the company's processes, the employees or the contractors must be certified by the Six Sigma certification belt system. The projects in manufacturing or service companies could be divided into two groups, the first group would be a project which has scope, cost and time needed to reach already known desired outcome and solution, while the second group of projects would be where the outcome and solution for the project is not known yet [7]. Six Sigma projects fall into the second group of project types. For the project to have a positive outcome, the tasks and analysis are done by certified personnel, who can be mainly certified in green belt certification, black belt certification, and master black belt certification [7]. There are more Sigma certification levels which can be seen in Fig. 3, but lower levels are not commonly certified as the entry level usually is green belt, which can be seen from the research done in [7]. Moreover, in most cases, the root cause of the problem during the project is not known until the analysis step is done. That is why Six Sigma projects can fail if there is a high number of mistakes made throughout the project, such as a lack of commitment from the top management, poor communication, incompetent teams, poor training and learning techniques, improper selection of process improvement methodology, and quality control tool usage [7]. The research done in [7] also highlighted that differences in countries and the evaluation of the belt system differ, as in some companies the Six Sigma project could be problematic with higher risk for resistance to change and poor communication in the company’s culture in Great Britain compared to other surveyed and analyzed countries. Therefore, proper selection of certified Six Sigma professionals, understanding of the company's culture, and evaluating risk factors are necessary for the success of a Six Sigma project.

Six Sigma belt certification can be divided into five belts. The first level of the Six Sigma certification is the white belt, which is mostly gained for entry-level employees, who are only introduced to the Six Sigma culture but are not actively working on the improvement projects [8]. Furthermore, the knowledge that is gained from white belt certification is wide and not precise, for any problem-solving tasks white belt certified professionals need engagement and help from higher-level belts, such as green belts or black belts [8,9]. The second level of Six Sigma certification is the yellow belt. These professionals have a deeper knowledge of Six Sigma methodologies and quality control tools, which are used for process improvement. Yellow belts are working together with higher-qualified Six Sigma professionals for various improvement and problem-solving projects, as they have a supporting role in those projects [8,9]. The green belt certification is given to personnel who have high-level skills in analyzing and solving problems with quality control tools. If the project scope is not too high, green belts can play a leading role for smaller-scale projects as they have a full understanding DMAIC process to find waste and eliminate defects [8,9]. Furthermore, quality control tools such as Failure Mode and Effects analysis (FMEA) and control charts are being used by green belt certified employees, who can have roles in the form of quality engineers, quality managers, and continuous improvement managers [9]. Fourth, Six Sigma certification is the black belt expertise, which is used to lead complex and large-scale Six Sigma projects. These experts can train others in Six Sigma principles while also having already mastered the Lean and Six Sigma methodologies [9]. Moreover, they have a high level of knowledge and skill not only in quality control tools and analysis, but the role requires a high level of understanding of management skills as black belt certified employees must manage the whole team throughout the project [8,9]. In addition, these roles are used when there is a need for a significant change and impact on a company’s productivity and efficiency. Finally, the last certification level is the personnel who have been a certified black belt for no less than five years or have been working with large-scale Six Sigma projects for no less than ten years [7,8]. Therefore, evaluating the project scope and what kind of team qualification is needed to complete the project is essential to have a successful output of the project, which in Six Sigma projects is to find the unknown problem that is causing waste or defects. In conclusion, there can be high level of consequences as Six Sigma projects could be shut down at the Measure or Analysis stages of the DMAIC if improper personell is used with the lack of leadership skills, which is displayed by black and master black belt certified proffesionals, although doing small scale projects the team lead could be lower level employee as the scope does not require high management skills.

Qualified Six Sigma professionals can have different expertise as the fields they are working in are differentiated. In scientific research [7], a survey was done with 1000 respondents, which showed that respondents were divided into the manufacturing sector, which contained 48.75% of LSS certified experts, and 50.25% in the service sector. The concentration of experts was evaluated to be 38.8% at the black belt level, while very similarly, 38.3% were at the master black belt level, and the lowest amount was the green belt level at 22.9% [7]. Although this research did not take into consideration the white and yellow belts, as it might not be that important, as Lean Six Sigma is usually applied in large-scale projects. This research also shows that the sample group had a very high knowledge of Lean Six Sigma methodology, and a high number of projects were done and led by black belts or master black belts [7]. Analysis done on the respondents highlights the saturation of

LSS proffesionals who are highly certified with a large amount of experience, this indicates that LSS application is done at a very high level with large scale projects as the least amount of certified proffesionals was green belts, who are utilized in teams and leading low scare and small improvement projects.

1.2. Lean Tool Usage in Production for Process Efficiency Improvements

Lean tools have been introduced and were first utilized in a car manufacturer, Toyota, which aimed to reduce waste in processes by identifying what creates the waste and how it could be eliminated. Lean methodology revolutionized how production processes were analyzed as the highest focus was to improve efficiency with continuous improvement while decreasing the non-value-added activities in the production [10]. Lean tools have been utilized not only in manufacturing companies but also in medicine, service providers, and the education industry [10]. As mentioned in [10], the five main Lean tools are used for process efficiency improvements, which consist of 5S, Kaizen, value stream mapping, PDCA cycle, and root cause analysis. Moreover, Kaizen is essential for Lean methodology as it trains employees to have lean thinking, which is eliminating waste through continuous improvement, which is small incremental changes, where the main goal is not only to reduce waste but also create value to the customer [11]. Kaizen is used with the involvement of all employees regardless of their level, fostering a culture in the company for improvement suggestions and innovation [10]. In Kaizen, there are many activities such as brainstorming sessions and data analysis, after which the implementation of small improvements is done for further benefits over time [10]. Moreover, this methodology is used to improve employee skill development and motivate the workforce for a more efficient and effective flow in production. 5S methodology consists of five steps that need to be used in the workplace, which consist of sort, set in order, shine, standardize, and sustain. These five steps, while looking like a simple tool, implementation in a large manufacturing company might be challenging. The first step is to sort everything in the workplace, which means to organize what is needed and what is not needed, thus removing any unnecessary items or equipment and only leaving the essential tools [10]. The second step is to set in order every tool and material that was left from the previous step, organizing them for easy access when needed, thus increasing efficiency by eliminating unnecessary movement [10]. The third step is to shine, which is to keep the workplace clean, promoting safety and ease of mind from a clean workplace [10,11]. The fourth step is standardized, which establishes the same implementation in similar workplaces, so that there would be less variation and more organization throughout the whole company, and the last step is sustaining, which is mainly for keeping the first four steps under control and maintained at the workplace [8,9]. The PDCA (Plan-Do-Check-Act) cycle is essential for finding problems in processes and solving them and is one of the fundamental initiatives that are done when there is a need to improve process efficiency and reduce waste [10]. PDCA is a continuous improvement tool as it is carried out in a cycle, continuously repeating [11]. PDCA is used to develop a new process or product design, design repetitive work processes, and implement process changes [10]. Moreover, the first step of PDCA is to plan, which is to find a process or an area where there is a high amount of waste and there is a need for improvement, then a plan is created for the change. The second step is Do, which is to initialize the change and test it on a small-scale basis [10]. The third step of the cycle is to check where the analysis of the results is done to generate feedback [10]. The fourth step act, which is to act based on what was learned, by standardizing successful changes and creating or revising the plan based on the findings from previous steps [10,11]. Moreover, the PDCA cycle is essential at the start of a lean project, where the planning step is very important for having a positive result at the end of the cycle, similar to in the Six Sigma DMAIC methodology [10,12]. Value stream mapping is the most important and powerful lean tool, which is used to analyze the flow of materials and information for the product from the beginning stage to the final stage [10, 12, 13]. Moreover, each step is mapped out and divided into value-adding and non-value-adding activities [10]. Nevertheless, this tool is used by continuous improvement specialists and managers to identify where the value for the customer in the process is created and where it comes from [11]. In value stream mapping, the flow of materials and information is done through flow diagrams, which give a visual interpretation of the current flow in the process [11-13]. Utilizing VSM properly, improving productivity, and most importantly streamlining the operations [12-16].

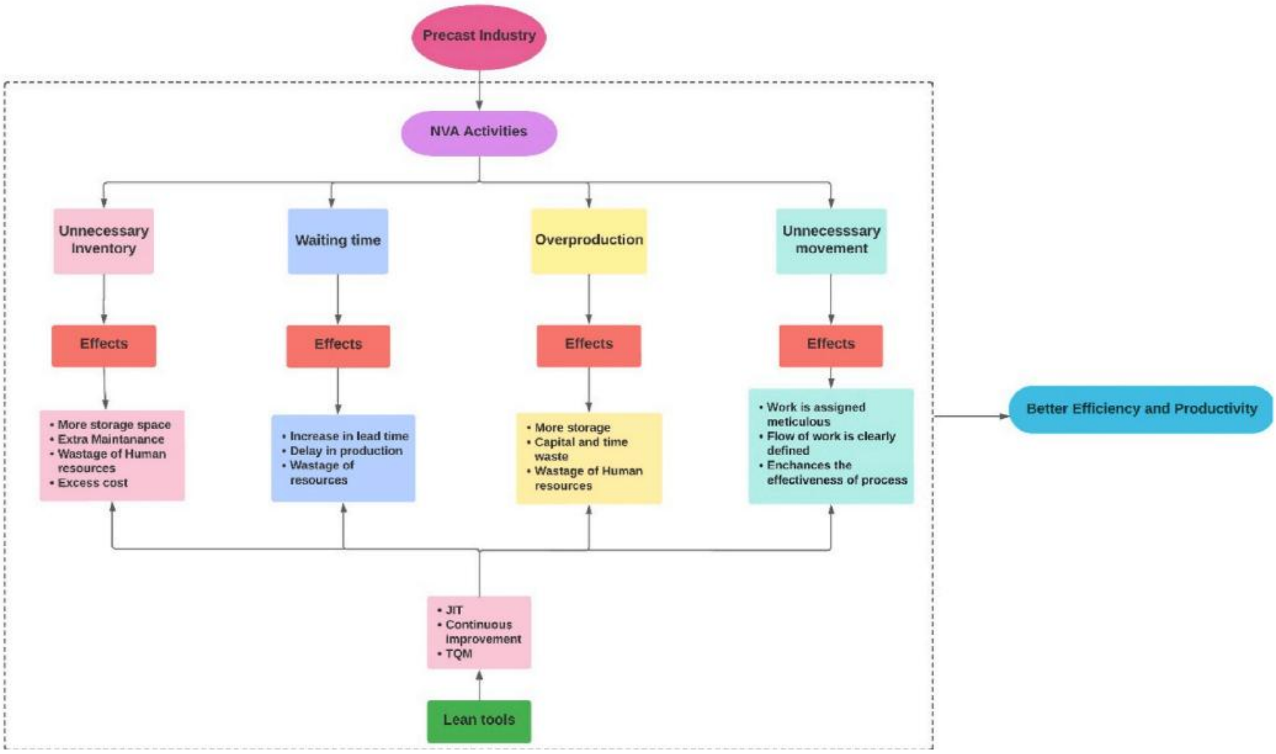

Fig. 4. Relationship Between Lean and NVA [16]

Lean tools are used to eliminate non-value-added activities. Non-value-added activities directly correlate with the eight lean wastes, which consist of defects, unnecessary waiting, transportation, overproduction, high inventory, motion that is not required, and overprocessing. These eight wastes are the activities that do not add any value to the customer or the manufacturing company. Although, according to [16] the mostly used Lean tools to eliminate non-value-added activities seem to be Just in Time (JIT), continuous improvement and total quality management. Moreover, activities such as unnecessary inventory, high waiting time, excessive production, and unnecessary movement do impact the process flow more than other waste [16]. The relationship framework between lean tools and non-value-added activities is shown in Fig. 4.

1.3. Lean Six Sigma Utilization in Various Processes for Defect Reduction and Efficiency Improvement

A new combination emerged from the utilization of Lean tools with the DMAIC cycle of Six Sigma, which is called Lean Six Sigma. While Six Sigma is used to reduce defects and improve process variation, lean tools aim to find and eliminate waste. While these two methodologies might have different goals, the combination of both can be very beneficial economically and sustainably to the company that implements the Lean Six Sigma methodology projects [12,13]. Applying Lean tools with the DMAIC cycle can be more beneficial to companies as results can have a higher financial impact on the company than applying basic seven quality control tools with the DMAIC cycle [12]. Furthermore, the structured approach while using the DMAIC cycle gives a concise understanding of the material and product flow throughout the company's processes [12]. Utilizing Lean Six Sigma projects in a company creates value for the customer, keeping the company at a competitive advantage compared to the manufacturers who are not using LSS for process operational efficiency improvements [12,13]. While companies are already using Lean tools to improve the efficiency of production, projects with Lean Six Sigma methodology utilization are quite new. As mentioned in [13], "Studies have reported that the use of Lean Six Sigma approach for waste reduction, production performance improvement and customer satisfaction improvements can be applied to various sectors such as manufacturing, education, banking, health". In addition, this shows that LSS is a flexible approach, which can be applied to various industries and fields, although the focus at this moment is on the manufacturing industry. Lean Six Sigma can be used to reduce quality control material usage, which was done in [12], while other approaches could be to improve process efficiency in the railcar manufacturing industry [13]. In conclusion, Lean Six Sigma is a tool that combines quality control tools to achieve the best financial, social, and sustainable approach for manufacturing companies.

The application of Lean Six Sigma can vary depending on the issues that the company is facing. Firstly, LSS can be implemented in company processes where there is a high amount of equipment breakdown, as this method would be used to analyze and improve the maintenance process in a manufacturing environment [14]. Furthermore, the application of quality control tools such as fishbone diagram, FMEA and 5 why's could lead to finding a problem which consists of improper maintenance schedules, introducing new maintenance plan with preventative maintenance and if the scale of the problem is large predictive maintenance techniques, could drastically decrease the amount of breakdowns and decreasing the repair costs, which bring financial benefits through properly maintained equipment and production effectiveness improvement [14]. In addition, LSS can also reduce environmental footprint as the utilization of waste reduction methods could significantly impact the resource usage, energy consumption, and unnecessary scrap in a production company. While analyzing the whole lifecycle of a product through various tools such as value stream maps and SIPOC diagrams, it can lead to solutions where the resource utilization would be improved, as more efficient production cycles could be introduced by eliminating non-value-added activities throughout the production from raw materials to the finished product, which arrived at the customer [13]. Moreover, application of the DMAIC cycle with lean tools can improve resource utilization effectiveness in a manufacturing company if the analysis of the main problems is the result of excessive defects, scrap generation, and non-value-added activities [12]. Finally, LSS applications are universal and can be applied to any process in the product's lifecycle.

Lean Six Sigma application is usually applied with tried and tested quality control methodologies and technologies. Furthermore, not all Lean Six Sigma projects are successful, and there is a high number of projects that are discontinued by the company [7]. This happens for the same reasons that were mentioned before, which are incompetent employees, no initiative from top management, and poor selection of the project scope and goals [7]. It is hard to persuade top management and project stakeholders to keep the LSS until the improvements are implemented, because there might be lack of understanding of the value that is being created through numerical value, because most LSS outcomes are unknown as the project deliverables are not specified, because the root-cause and non-value-added activities are not yet defined and solved. Moreover, the fourth industrial revolution is important to process analysis and improvement, because as stated in [15], Industry 4.0 and LSS complement each other, as the technology which is used in Industry 4.0 could have positive results with LSS application. Furthermore, Industry 4.0 techniques could be used for real-time process deviation corrections, where the usage of digital twins and IoT devices, through production processes, could be implemented [15]. In addition, improving data collection with Industry 4.0 technology, the analysis step of LSS DMAIC could be greatly impacted as projects would have more precise and organized data, such as measurements, which would affect the efficiency of the project, from which better solutions could be provided. Moreover, with process simulation software, the analysis of Six Sigma could be greatly improved, as brainstorming sessions and suggested implementations or improvements, which could be checked and tried first in simulation environments, and the most efficient and economical solution could be implemented. Finally, companies that have applied LSS through already existing methodologies have faced positive economic and sustainable results, but introducing Industry 4.0 to the DMAIC cycle might yield more efficient and beneficial results.

1.4. Chapter Summary

Quality control tools are essential to achieve a competitive advantage for a manufacturing company, as customer quality requirements and standards are increasing. Six Sigma is a method of process variation improvement and defect reduction through the whole life cycle of the product. Six Sigma can be applied to improve maintenance, changeover, transportation, storage, injection molding, milling, and grinding production processes. Lean manufacturing tools have a significant impact on process efficiency throughout the whole production process. Utilizing continuous improvement and value stream mapping is necessary for any modern manufacturing company. Lean Six Sigma combines both methods to not only reduce defects and improve process variation, but also improve process efficiency, resulting in a higher chance of project success rate. Finally, Industry 4.0 should be implemented and used in conjunction with LSS methodology as it increases the productivity and efficiency of the improvement project.

2. Lean Six Sigma DMAIC Application Throughout Different Industries

Lean Six Sigma methodology, with the usage of quality control tools, is necessary to have a properly defined and standardized process in companies. Moreover, as mentioned in the previous section of the research, Lean Six Sigma can be used in various ways in manufacturing companies for the financial benefit of the company. Nevertheless, this methodology can also be applied to other companies' processes, such as improvement on warehousing and logistics, customer service, and research and development processes. The methodology is universal, and for this reason, the LSS approach is used in other industries not related to manufacturing, such as healthcare, telecommunications, and IT services. In conclusion, the application of LSS varies depending on where it is applied, and each application is unique, as the environment in which it is done is vastly diverse.

2.1. DMAIC Approach in Various Companies for Efficiency Improvements and Defect Reduction

LSS process analysis methodology can be used to improve the call center department process for better efficiency and customer satisfaction. As mentioned in [17], the rising competition in the energy sector is always growing, while it is already at a high level. Moreover, this case study has shown that there is a possibility to apply Lean Six Sigma methodology in the service sector [17]. Moreover, the project was utilized in a Call Center through the interaction of the company's customer service employees with the customers, where communication was done through emails and calls [17]. Furthermore, the LSS approach was chosen because the market is very diversified and has various customer preferences, and there is a need for an agile and rapid change to the processes as new services are introduced [17]. Firstly, in the project for LSS in the energy service sector, the definition of current problems that the company is facing was made, which were indicated to be that while the company receives around 60 thousand calls a month, only 2.87% of those calls are efficient and actualized [17]. Moreover, the project team, which was made from a green belt team, a supervisor of Operational Excellence, and a Process owner, was formed to achieve a goal of 10% actualization through calls and emails [17]. The project team created a project charter to convince them why the LSS application is important to the company and the effectiveness of the customer service. The main key performance indicators were concluded to be average customer waiting time, average time for the call with the customer, percentage of answered calls, and the number of contacted customers per month [17]. In conclusion, the preparation of a project charter is essential as the definition of targeted goals could vastly impact the efficiency of the project application.

LSS was applied by using the DMAIC approach, where each step was done to achieve a certain target. In the Define stage the business process of customer interaction from start to finish were evaluated and mapped by using a SIPOC (Supply, Input, Process, Output, Customer) diagram, where it was defined from the inputs from suppliers, what processes were done to get the outputs and who are the customers [17]. In the SIPOC diagram, the suppliers were indicated to be the applications, tools, and different customer types that were communicating with the call center employees. Moreover, inputs were shown to be problems from customers, while through phone system it was identified called and IT system the information of the customer [17]. The process was detailed in three parts, which consist of input collection, the main process, and delivering the outputs. The definition of the main process was not fully defined, but for customer services, it mainly should be the information gathered from the customer, clarifying and checking the problem, and providing solutions or solving the problem

[17]. Output was identified to be some of the solutions that could be provided by customer service, while the last part, which was identified to be what the customer is, was the customer and service unit. Moreover, in the define stage of evaluating and defining the current process, it is essential to understand what the main inputs and outputs of the process are to have a better understanding of the measurements that will be done in the latter stage.

The measure stage is used to gather the key performance indicators for further analysis in the project. The measurements were carried out using Minitab 18 as the collected data could be used to see the differences between customer service employees and the capability of the process [17]. The measurements were made to the call duration between three operators in the Call Center of the company, it showed a high variation and fluctuation of time they took with customers in the call, where the lows showed less than 100 second call time while some peaks were showing higher call times almost reaching 600 seconds [17]. The process capability report indicated that there are quite a lot of fluctuations between the operators, because operator 3 mainly had an average call time lower than 3 minutes, while operator 1 had a lot higher average call time, which inclined that the reasons for higher call time and high variance should be identified [17]. Cpk was identified to be not being enough, indicating that there are problems with average call time. In conclusion, the company has a high fluctuation in its process as every customer is different, and the issues they are facing can be very diverse, creating inconsistencies in the process, capability, and variability.

Analysis and Improvement stages were done to identify and solve the main problem in the Call Center. By using quality control tools, the problem of long call times was indicated to be not the problem of the operator, as the main factors for very long call times were identified with customers calling to have issues with the bills or billing [17]. To improve the current problem that was identified, a new deployment diagram was suggested [17]. Improvements were made to the simplification of data, which should impact customer data actualization. Moreover, standardized scripts and procedures were implemented to have an overall higher quality for customer satisfaction and a standardized way of solving customer billing problems [17]. Furthermore, the implementation of ANOVA / I charts for data analysis and monitoring. Moreover, in the control stage, the documentation of standard work was done, and implementation of statistical control tools was introduced to monitor the whole process variability [17].

Suggested improvements for the Call Center service process can greatly impact the performance of the process. As indicated in [17], the results after the improvement were measured after 3 months, which showed a positive outcome. Moreover, the actualization has increased from 2.6% to 20%, which is a lot higher than was intended goal for the project charted as it was identified to be 10%. Although the research has not provided solutions for the calls for billing problems, the indication of the bill issue was passed on to the company, which was mentioned to be optimizing the system to reduce calls for this specific problem. Nevertheless, this case study has shown that LSS can be used outside of the production industry to have improvements in processes. Moreover, this case study has shown that sigma level calculation and indication are not necessary to reach a targeted goal for improvements, although in the production process, it should be essential if the production defects need to be evaluated. Although there was a lack of lean tool application in this case study, the methodology that was used was the standard Six Sigma DMAIC approach, without evaluating value-adding and non-value-adding actions. In conclusion, LSS is a great tool to improve a customer service process, indicating high value created for the company through problem-solving and issue identification.

Lean Six Sigma application can be used for improving maintenance and implementing sustainable practices in the process. Firstly, the LSS application and usage of appropriate tools can impact the maintenance efficiency in a manufacturing or other industry. The impact of maintenance is very important to all companies' processes, which consist of production, logistics, safety management, and occupational health [18]. Moreover, having proper maintenance directly impacts the performance of the production and the productivity of the employees, as inconsistencies in machinery maintenance create critical breakdowns, random shutdowns, and defect generation throughout the production line and its processes. In case study [18], it was mentioned that the research was done in a leader in production, which manufactures floor coverings. Furthermore, it was mentioned that the production area consists of 23 machines, where the main goal was to apply LSS in this production plant to evaluate the maintenance plan and suggest improvements and solutions for the granulating, extrusion, printing, and finishing machinery and processes. The problem in the case study that was currently defined before the application of LSS related to many failures with the machines, reducing the OEE and availability of the machines in the manufacturing process [18]. Moreover, the stoppage of machine working time means a high financial repercussion to the production company as it is directly related to the costs of finished goods, therefore, LSS application was done for this purpose. As the goal was set to improve production machinery efficiency, similarly to the previous case study, the problem analysis was done by applying the DMAIC cycle of Six Sigma. In conclusion, it is noted that companies are still facing issues in production machinery, which causes financial losses, and the improvement tool that can be chosen to solve the problem is LSS.

Define stage of LSS can be used to determine the impact of the methodology application by setting the needed goals for project implementation. In the case study [18], it was defined that the elimination of constant machine failures could be reduced by 40% in the span of 6 months. The application was done in the same manner as in the Call Center process improvement study, as the SIPOC diagram was utilized to fully define the process that will be measured and analyzed [18]. Although SIPOC diagram might be the same tool, the contents of it vary as the supplier inputs and outputs are significantly different than what was provided in the case study done for an energy service provider. Inputs were defined as machines, maintenance workers, and machine workers, while the process that was analyzed was the maintenance process that produced the outputs that were defined as available machines for production [18]. Moreover, the measurement stage was used to gather data from a 2-year period with 1120 observations [18]. The gathered data was first assigned to certain processes, which were defined as G1, G2, G3, G4, and G5. It was shown that the longest failure time was measured to be at the G5 area, which can also be seen in Fig. 5, consisting of 26680 hours of failure during the 1120 observations [18].

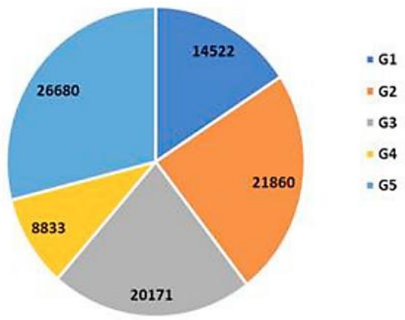

Fig. 5. Failure Time For 5 Processes [18]

For further measurements, the failure duration time was split into an observation interval, which showed a high variability in the inconsistencies, as in some observations the failure time was less than 50 hours, while in other intervals it was as high as 985 hours [18]. Although further analysis the high points were removed, and the average failure time was observed to be at 240 minutes, as the highest number of failures was shown to be in the interval from 16.5 to 246.5 minutes [18]. In conclusion, the define and measure stages in some areas are like other LSS applications, but by analyzing a different process, the measurements and process definition vary greatly.

Maintenance inefficiency analysis differs from the production process analysis for improvement. Firstly, in case study [18], no quality control tools were applied for the analysis stage as the approach significantly differs from previous studies. Moreover, to identify the factors that could have an impact on critical to quality factors that were defined by the Shapiro-Wilk test was used in conjunction with the of Kruskal-Wallis test and Spearman tests to determine the main factors impacting CTQs and the root cause of those factors [18]. Furthermore, the application of these tests provided the results of the most common failures that occurred on machines [18]. The main problems that were defined were identified as: low work experience of operators, TPM was done on the machines less than 6 months ago, etc. For the root cause of the problems Ishikawa diagram was used, which identified the main problem to be the improper implementation of autonomous maintenance and preventative maintenance activities [18]. Nevertheless, the application of the Ishikawa diagram is known to be very effective in the analysis step of the DMAIC cycle, which is seen in the current case study example, as the root cause of the problem could be found where improvements could be suggested. The main root causes of improper maintenance were lack of training for operators that were utilizing autonomous maintenance (AM), lack of monitoring of the AM performance, inadequate scheduled preventive maintenance plans and actions, high overload of machines in production, and differences in AM standards for the same type of equipment [18]. The application of the DMAIC cycle varies depending on the process that is analyzed and the main problem the process is facing, but some quality control tools like the Ishikawa diagram have been proven to be effective in finding the root causes of the problem.

Improvements by utilizing proposed solutions for maintenance plans can greatly impact machine downtime in production processes. Furthermore, the proposed solutions in [18] were identified to be periodic training for employees with implementation of new training plans, delevopment of monitoring method for autonomous maintenance and creating a procedure for solving problems after reported problems from autonomous maintenance and preventive maintenance, standardization of autonomous maintenance for the same equipment type and implementation of periodic audits [18]. Moreover, a schedule was presented on when the improvement actions should be implemented in the maintenance process, starting with developing periodic training and ending with the periodic audit implementation. Nevertheless, in the control stage of DMAIC in maintenance process the suggested improvements were done as the schedule suggested, although it was mentioned that not every suggestion for the improvement were implemented as the company already noticed the benefits, where machine down time has been reduced and reported problems with autonomous maintenance have been decrease, although measurement figures were not given as not all improvements were implemented and longer time was needed [18]. In conclusion, the benefits that the company has yielded from LSS application for maintenance processes have been noticed to be positive, although, as mentioned before, the results can be different if the same solutions were applied in other manufacturing companies.

While Lean Six Sigma methodology is beneficial to customer service and the maintenance process, the highest benefit could be achieved by applying it to a production process in a manufacturing company. Applying lean six sigma methodology to production processes, in the first stages of the project, the definition of the analyzed process should be done through creation of the current or present value stream map [19]. Compared with the studies that were analyzed before, the main change is that there is an evaluation of value-added time and non-value-added time. The analysis in [19] was done for a paper production company to increase manufacturing process efficiency. Moreover, the way the methodology is applied highly differs as the focus of the research and implementation was done more numerically, as the measurements gained from evaluating which activities create value and which do not, can provide the statistics for process cycle efficiency calculations [19]. Although the researchers have not named the DMAIC phases in the Lean Six Sigma implementation, it still follows the cycle as firstly, in the Define stage, the value stream map is created to have a deeper knowledge of the current company's process. Value stream maps are quite like SIPOC diagrams as they provide the same entities, such as supplier, inputs, processes, outputs, and customer, but the information throughout the whole process is highly defined with more data provided [19]. In conclusion, the Lean Six Sigma application in the define stage could also implement Lean tools to have more numerical data for process efficiency evaluation.

The measurement phase of LSS can be utilized not only to evaluate process efficiency but also to determine the wastes that are made through defects in the production line. Moreover, in the case study [same], the measurements were done through process cycle efficiency calculation, which were indicated to be at 23.4% and are lower than the target benchmark of 25% [19]. The process cycle efficiency was calculated for the whole value stream map from supplier to customer. Furthermore, this indication provides a better understanding that there is a higher amount of non-value-added time activities than value-added activities [19]. Nevertheless, takt time of the production line was calculated to be at 4.11 seconds for one piece, which indicates that the production process is very fast paced [19]. Moreover, calculations were also done to evaluate the non-conforming products in the production line, where process stages such as plate cutting, printing, trimming, and stitching were evaluated to have quite a high gap to reach the targeted six sigma level of 6 [19]. Furthermore, to evaluate the Sigma Level, the calculation should be done through defects per million opportunities such as was done in the research of a paper production company [19]. The measurements of downtime were done for the AB production line, which indicated that the production line has a 32.64% downtime, and indicated that one-third of the production cycle consists of downtime, which is a clear indication of the low process cycle efficiency [19]. The evaluation that was done in the measurement phase indicates two main measurements, where one is focused on process efficiency, while the other is focused on defect production in the process. In conclusion, the measurements were made very precisely, which provides a better view of the process and its waste generation.

The analysis and improvement phase was used to find not only the root cause of defect production but also the inefficiencies in the process. Nevertheless, the Pareto chart was used for the evaluation of downtime causes in the process, and the three main issues were identified to be ink wetting, plate misalignment, and job misalignment [19]. Moreover, throughout the analysis stage the constant communication between LSS team members and production supervisor have identified certain issues that were reported to be a delay or insufficient raw materials for the production which generated non-value-added time, the suggestion of Kaizen in terms of Kanban and Poka-Yoke were suggested to improve the monitoring and measurement of the supply and warehousing. Moreover, other lean tools such as 5S were suggested to improve the non-value-added activities throughout the whole production [19]. However, the suggestions that were provided by the implementation of lean tools the research did not provide how the suggestions were implemented. Examples through pictures before and after 5S application are necessary to understand how lean tools affected the workspace to improve efficiency, which was not provided [19]. Moreover, kaizen throughout kanban implementation also did not show how the lean tools were used. Further analysis was done using a root-cause and effects diagram, also known as a fishbone diagram, where the main points were evaluated to be work organization, method, man, and machine for the non-conformity causes **[**19**]**. However, the root-cause indications were not provided after the root-cause analysis was done. Nevertheless, the improvements that were made through the usage of lean tools suggest that the results should be positive as it is indicated in [19], process downt time was reduced from 32.64% to 11%, which had a great effect on the process cycle efficiency as it increased from 23% to 40% after Kaizen and work standardization [19]. Moreover, the overstaffing problem was reduced from 33 to 16, which is a great indication, as the costs were reduced for the paper production company. In conclusion, the application of LSS in analysis and improvement phases is the most essential part of the project, as the results directly correspond to process improvement suggestions and earlier phases of the DMAIC cycle.

Lean Six Sigma application in the textile industry is not that well documented, although some applications have been successful. As mentioned in [20], there are some LSS successes in the literature, where one study was analyzing dyeing and finishing problems. Moreover, it was reported that the application of LSS in a large manufacturing company that produces terry towels in dyeing fabric showed great success financially, as the cost savings were estimated to be around 50 thousand dollars a month [20]. In addition, the second application of LSS was done at Unify, which is a global producer of multifilament polyester [20]. The success of the LSS implementation was imminent as the company’s efficiency increased from 20 to 40%, depending on the departments in the company [20]. In addition, the research done in [20] showed the application of LSS to a company that is a leading manufacturer of polyolefin and bi-component fibers, which are used in the textile industry. In addition, it was mentioned that the research team had communication with the company’s project supervisor, who had Master Black Belt LSS certification. In the define stage of the project, the goal was devised to be a reduction of the changeover time for the company, as the current changeover time from PE fiber to PET had a high average, as it was indicated to be at 15.5 hours [20]. Measurements were made through tools to create a detailed process map, fishbone diagram, and failure mode and effect analysis [20]. Although, in this case study it is noted that there are inconsistencies related to other case studies, as measurement stage should not have such tool usage which is used for root-cause analysis in the analysis phase of the DMAIC application [20]. Moreover, the analysis phase was used to analyze waste and variation through detailed process maps, while also implementing a lean tool called single minute exchange of die (SMED) system to identify internal and external activities for the changeover process [20]. Application of the analysis tools for the changeover process, some root causes were found, such as improper changeover process steps, creating non-value-added activities [20]. Moreover, in the improvement phase, new suggestions were implemented where operators were trained in new standards and the changed process [20]. In addition, a checklist was used for operators as the production process could be monitored more precisely. Finally, the last improvement was made through work standardization, where the changeover process was documented to help operators work efficiently with the current process, where spinneret installation was reworked as it caused leaking issues [20]. The improvements were shown to be successful as the average changeover time was reduced by 9.85 hours, leading to financial benefits for the company by utilizing resources more efficiently and improving the whole production cycle efficiency, as per cent reduction reached the number of 37. In conclusion, LSS applications in the textile industry are rare, but the application is beneficial as the improvement could be done not for the standard production process but for the changeover process, which in the textile industry is of high importance as the changeover times go over 10 hours.

The application of LSS methodology has grown tremendously in small to medium-sized enterprise manufacturing companies. As mentioned in [21], there has been a high rise in new publications and scientific journals since 2008, as the need for production efficiency and waste minimization is growing yearly. Nevertheless, it is also mentioned that the number of publications which consider LSS applications is still low, which indicates that there needs to be more research done in the small and medium enterprises as most LSS applications are done for large enterprises with a big project team and a large number of standardized processes [21]. Moreover, the number of scientific journals is related to which country it was written, as the highest publisher amount came from the United Kingdom with 25.8%, while India was 22.6% [21]. In addition, it was noted that none of the scientific journal publications were done from Lithuania, indicating that there might be a low amount of LSS application in this country, as manufacturing processes might not be up to par with other countries [21]. Nevertheless, the data shown in [21] indicates that there are a vast number of companies where the LSS could be applied. In conclusion, LSS methodology is usually applied to large entreprise businesses where processes are fully defined and LSS projects are more efficient, although there has been a rise of LSS related scientific journals for small to medium enterprise manufacturing companies, indicating that the methodology is necessary to have an efficient and effective production process in a company.

There are various benefits and motivational factors to implementing LSS in manufacturing processes. As mentioned in [21], the benefits of LSS applications in small to medium manufacturing enterprises are indicated to be a reduction in reduced operational costs, quality improvements for the products and production machines, increased throughput which indicated better effectiveness, reduction of downtime and efficiency increase, increase in profits, reduction in lead time, better employee morale. Most of the scientific publications of Lean Six Sigma application only show success, as there might be bias for the researchers and publicators, as LSS projects usually need a high number of resources, which indicates that publicizing LSS failures is not beneficial for the researchers. Moreover, the failures of published LSS projects would give even better insight and areas of improvement, thus improving the application furthermore.

2.2. Methods and Tools Used in the Application of Lean Six Sigma for Process Efficiency Improvement and Defect Reduction

Lean Six Sigma methodology is used with various quality control tools and techniques to achieve benefits for the manufacturing company. In each phase of the DMAIC cycle, certain tools and methodologies have been observed to be mainly used. Therefore, further application techniques for process improvement and cycle efficiency evaluation will be used to define the current process in a manufacturing company. In the Define phase of the DMAIC cycle, the main tool that will be used is the Value stream map, which indicates the current flow of the whole production from the supplier to the customer, where the indication of bottlenecks can be done. The value stream map for food manufacturers was made for whole manufacturing processes, indicating processes such as filling, cooking, mixing, forming, baking, and packaging in which total lead time was indicated to be 491 minutes and total value-added time at 325 minutes [22]. Moreover, non-value-added time was shown as material, human movement throughout the processes, which do not create any value. The takt time was indicated to be at 0.487 pieces per second. In addition, a visualization of value stream maps is shown in Fig. 6 while most value stream maps are created similarly, there can be differences in the diagram such as done in [13], where value stream map is done more simply, although main numerical measures such as lead times, value added time, cycle and changeover time are still indicated throughout the whole production.

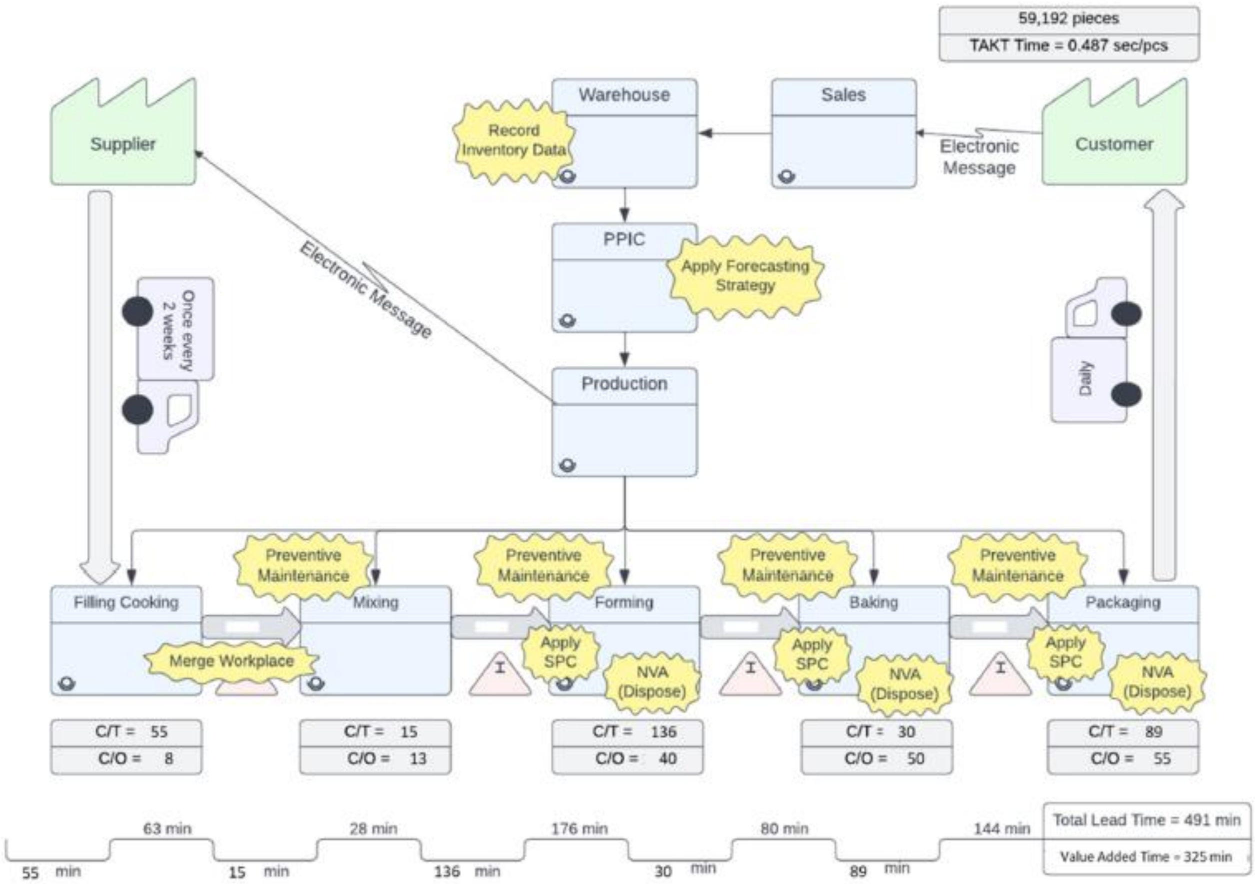

Fig. 6. Value Stream Map for Food Manufacturing Company [22]

Cycle time for the filling cooking was indicated to be 55 minutes, while changeover time was 8 minutes, indicating that while cycle time is high, the changeover time is not that big of an efficiency issue [22]. Moreover, in baking, it is exposed that changeover takes longer than the cycle time, which might be the first part where efficiency should be analyzed and improved if changeover could be reduced [22]. Finally, this is a great Lean tool where the definition of which company process needs to be analyzed will be selected through justification from numerical value and the flow of the production.

The measurement phase is the most important part of the DMAIC cycle. Moreover, in the measurement phase, the methodologies that are mainly used are calculations of defects per million opportunities and process cycle efficiency calculations. These two main measurements indicate the effectiveness of the process and the number of rejected units that show the process sigma operating level. As indicated in [13], to properly calculate process cycle efficiency for each of the processes, value-added time and lead time need to be indicated. Furthermore, Present Lead Time can be calculated by adding value-added time with non-value-added time, while process cycle efficiency is calculated by dividing Present lead time by value-added time, thus getting a percentage of valuable time in the production [13, 22]. The formulas are presented here:

$$Process\ Cycle\ Efficiency = \frac{Total\ Value\ Added\ time}{Total\ Lead\ Time}\ x\ 100\%, \quad (1)$$

$$Total\ Lead\ Time = Value\ Added\ Time + Non\ Value\ Added\ Time, \quad (2)$$

Measuring the PCE is essential if there is a need to improve the process. Moreover, it is one of the main tools that is being used for the Lean tool application in a production process, as identification of non-value-added and value-added activities is the necessary step to reduce the lead time and improve the cycle efficiency in the process. Although, Lean Six Sigma measurement phase can also be used to have statistical data from the measurements made to the product, as mention in [23], the measurements were done on the product itself by using measurement tools such as Tinius Olsen H10KS for tensile strength, weighting of the specimens were done by using T-scale from Neksten laboratory and dimension measurements were done by using electronic calipers Mitutoyo. In addition, these measures were taken to identify current inconsistencies and variances with the product itself and not the process. Nevertheless, measuring the variances in the produced product dimensions or weight can indicate that there is a production problem in the process, where inconsistencies arise from various root causes, therefore, these methods are more likely to be used in defect reduction and process variability reduction. The measurement tools that were used for the LSS project in the 3d printing industry can be seen in Fig. 7, where measurements were taken of the product with standardized tools.

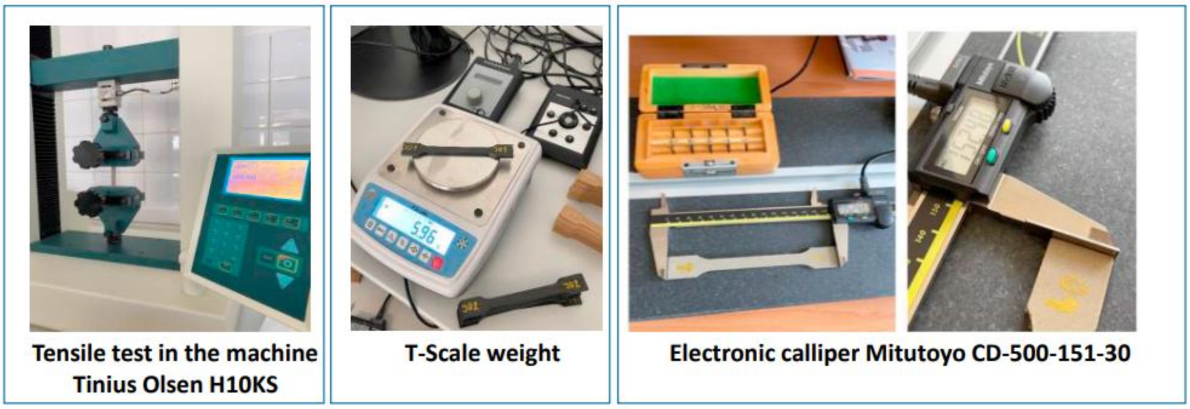

Fig. 7. Measurement Tools and Systems Used for Product Evaluation in the 3D Printing Industry [23]

For Six Sigma projects, a measurement phase is usually done with the calculation of Defects Per Million Opportunities (DPMO). Furthermore, the calculation of DPMO needs correct statistical data that is derived from the manufacturing facility, as the main influence is the rejection rate and the number of defects that can be found on one product [4-6]. In addition, LSS is not all about increasing efficiency, as reduction of defects and variability in the process can also bring significant benefits to the manufacturer [4-6]. The formulas needed for the calculation of DPMO and sigma level can be seen here:

$$Defects\ per\ Unit = \frac{Number\ of\ Defects}{Total\ number\ of\ units}, \quad (3)$$

$$DPMO = \frac{Total\ Number\ of\ Defects\ in\ Sample}{Sample\ size\ x\ number\ of\ defect\ opportunities\ per\ unit\ in\ the\ sample}\ x\ 100, \quad (4)$$

$$First\ Time\ Yeld\ (FTY) = \frac{Number\ of\ good\ units}{Total\ Number\ of\ Units\ entered}\ x\ 100, \tag{5}$$

Measuring DPMO in the production process is essential to determine the root cause of the defects that are causing the high rejection rate. Furthermore, the usage of LSS combines measurements such as process cycle efficiency, non-value adding activity and value adding activity times with the calculations of DPMO and Sigma level, therefore indicating what is critical in the process and if the efficiency is the main problem of the process or a high rejection rate in certain number of defects. Furthermore, the option of applying both generates the best outcome of the LSS project, as the most effective path is chosen for the financial benefit of the manufacturer. Nevertheless, either option is great considering the time for a project it takes to measure and gather the data for both options. In conclusion, the measurement phase can vary depending on the project scope and the defined goal, as the process could be analyzed through efficiency or rejection rate, and variability.

The analysis phase is used in conjunction with quality control tools to find the root cause of the problem or inefficiency in a production process. Furthermore, most LSS applications in analysis phases use Pareto charts to find the main issue from the measurement phase, either in defects or in waste generation in production. The example of a Pareto chart for both use cases can be seen in Fig. 8, where charts are divided for defect generation A and waste generation causes B.

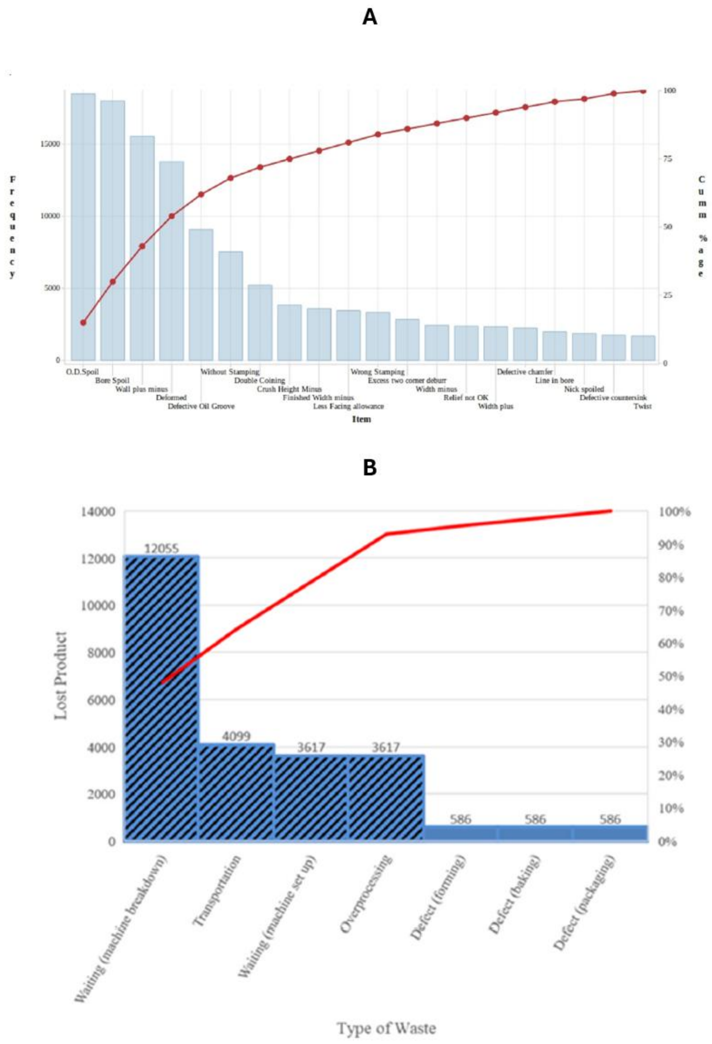

Fig. 8. Pareto Chart For Defect Generation, (A) and for Waste Generation, (B) [5, 22]

Furthermore, the chart is addaptable for both situations as the waste can be divided into certain categories such as transportation, wating from breakdowns or machine set up whereas for defects the frequency or occurrences of them can be indicated in where the most critical number of defects generated are on the A chart on Fig. 8 [5, 22]. Moreover, the main inefficiency in [5], from Pareto chart could be visualized as high waiting time from machine breakdowns, while the biggest defects in [22] were indicated to be O.D. spoil which creates marks on the outer diameter of the bearing and bore spoil which is also a visual defect on the bore surface. Finally, the Pareto chart is a very powerful visual tool that indicates the main issues in the process through defect or waste generation

To find the root cause of the problem that the process is facing, a fishbone diagram is necessary. Furthermore, the Ishikawa diagram, also known as the Cause-and-effect diagram, is a tool where the main problem is indicated, from which five or six different sections of possible causes are made, which are usually indicated as method, machine, measurement, environment, manpower, material, and management. Furthermore, as with the Pareto chart, the fishbone diagram could be made for both outcomes, which are either low process efficiency or a generated defect. Furthermore, an example of both applications of the Ishikawa diagram could be seen in Fig.9 as on the A diagram the fishbone diagram was created for low process cycle efficiency in assembly process, while in the B diagram the cause-and-effect diagram was created for high mold temperature in the production of car parts [13, 24].

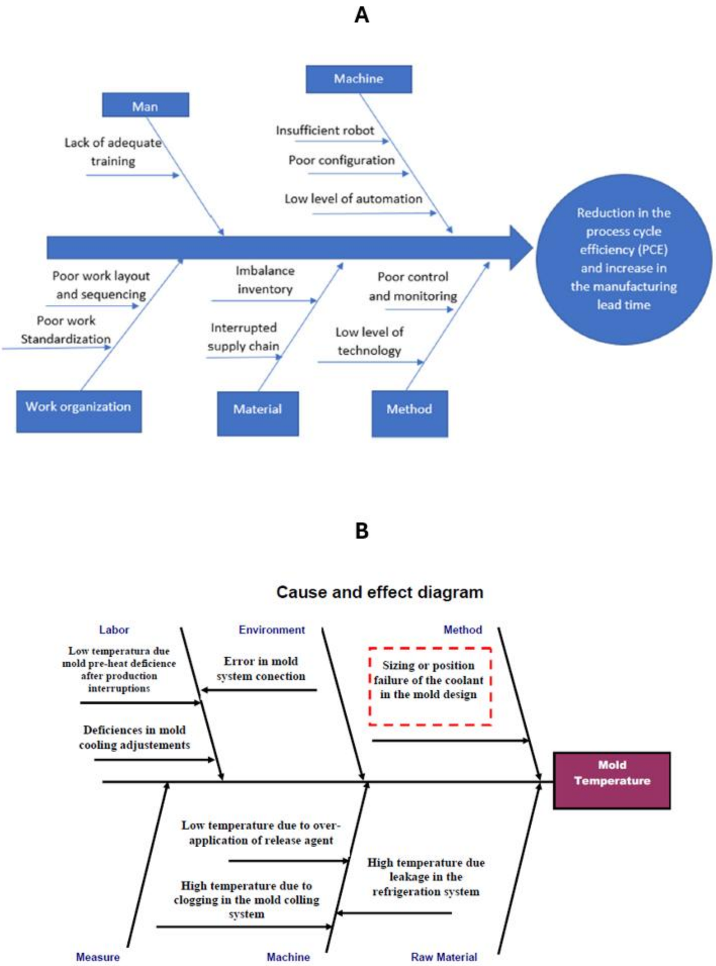

Fig. 9. Cause and Effect Diagram for Low Process Efficiency, (A) and Root-Causes diagram for Defect Generation, (B) [13, 24]

By going through various causes, from machine to method, it is possible to identify certain strains of the root cause from insufficient maintenance of the machine to the inefficient method that is being applied in the process, even environmental changes and conditions can cause the indicated problem in the production process [19-24]. There are also various other tools used in analysis phases, although it differs drastically depending on the application, whereas in [13] the application of SMED analysis was done to divide the value added activities in to interal and external, which is usually mostly used for improving the changeover process, where some activities could be done without shutting down the machine for the changeover, while other are done when the line is not currently active, during the changeover. The benefits of SMED are substantial as it increases machine capacity, reduces waste during changeover, standardizes process and consistency, lowers production cost as there is less downtime [25]. In addition, the 5 whys method could be used with a cause-and-effect diagram, where for each of the found causes, five why questions would be made that would provide an answer to where the root cause is located [6]. Moreover, most technical problems are usually found to be made by the human factor or issues in the process, this is why the five whys methodology is a great tool to narrow down the issue to its root cause [26]. In conclusion, there are various methodologies and ways of finding the root cause of the problem in the analysis phase, but in almost all instances, the Pareto chart and fishbone diagrams are used to define and further analyze the process, thus finding the root cause of the inefficiencies or defects in the production line.

The improvement phase is different for every process application. In addition, if the process is analyzed for defect reduction, the improvements that are made vary, as in some instances the improvements are made in the maintenance department, introducing preventative maintenance practices to improve machine downtime, because of the high number of breakdowns during production [5]. Moreover, improvements could be suggested for the equipment itself, introducing new technologies and add-ons as was done in [4], thus reducing the defects of joint cracks from the incorrect molding process. Furthermore, the improvements could be related to the standardization of work in the workplace, which can be alleviated by implementing lean tools such as 5S and ABC analysis to organize the workplace, minimizing the waste and bottlenecks in the electronic production process [27]. In addition, in [22], the improvements were suggested to be heavily based on lean tools such as Kaizen and 5s, where Kaizen is meant for a continuous improvement methodology for further efficiency increases. In addition, the improvement plan for kaizen is shown in Fig. 10, where the approach starts from the management vision until it is fully adopted by meticulous planning, monitoring, and development [19].

5S methodology is a great tool to reduce employee errors and increase efficiency in the process. In addition, the 5S technique reduced waste in the process as it is sorted into five steps, as the first step is to sort the parts and tools in the workstation and eliminate unnecessary items from it [13]. Moreover, the second step is to set in order the tools, where they are easily visible and accessible for the operator, reducing unnecessary hand movement or walking during operation [13]. Furthermore, the third step is to clean the entire workplace, which is essential for safety, where dangerous or hazardous materials are always cleaned or removed after work is finished or started [13]. The fourth step is to standardize the work procedures and activities, as was done in the case of the [13] assembly process. Finally, the fifth step or rule is to sustain the new practices in the workplace, maintaining the standard by doing weekly or monthly reviews of the workstations [13]. In conclusion, the improvements for the process could be achieved by improving the equipment and reducing the defects, or by implementing lean tools such as 5S, Kaizen, for not only improvement during the LSS implementation, but also setting a continuous improvement thinking in the production.

Fig. 10. Framework of Kaizen Implementation in the Food Production Industry [19]

The control phase is used to ensure that the suggested improvements are maintained, and the process performance is rated positively. Moreover, in the control phase a development of certain monitoring systems or plans are developed to control the improved process [17]. In certain aspects control phase is not defined as in [19], but it can also be a part of the results that were monitored before and after the LSS implementation [23]. In certain cases, the control phase can be used to standardize the results and reflect on the encountered problems in the processes, which provides feedback from team members on where to improve in later improvement projects [23]. The methodologies that are usually used in the control phase are the same lean tools that were used in the previous improvement phase, as Lean tools are usually meant to be used with continuous improvement, they also go under the control phase, as further improvements could be made in the future. In conclusion, the control phase sets the basis for further development in the processes by implementing monitoring techniques or technology while also showing the achieved results of LSS implementation in the process.

2.3. Comparison of Achieved Results of LSS Implementation in Various Industries

The results of LSS implementation vary depending on the current process cycle efficiency and defect rate. Nevertheless, the application of LSS in the paper production company has shown great results in improving the process cycle efficiency from 23% to 40%, which is an improvement of 17%, as mainly the lean tools were utilized as the improvements [19]. Moreover, the LSS approach in food manufacturers also had positive results, as the researchers indicated that the process cycle efficiency increased from 66.19% to 70.98%, which is an improvement of 4.79% and is a lot less than the improvements made in the paper production company [22]. Furthermore, the results that were attained from LSS implementation in electronics manufacturer are also rated positively as the process cycle efficiency increased from 31.37% to 35.29% as the increase reached 3.92%, considering that the process has already a low process cycle efficiency it was expected to reach a higher increase with the implemented suggestions, indicating that the project had a shorter deadline compared to the previously analyzed scientific publications [27]. In addition, the research that was done for LSS implementation in waste reduction of brake lining products indicated an improvement of process cycle efficiency from 26.85% to 35.33%, which is an improvement of 8.48%, resulting in a greatly improved process [28]. As seen in Fig. 11, the process efficiency improvement varies from each implementation, while the average improvement is calculated to be around 8.54%. In conclusion, the improvements that were done are positive although it varies from 3.92% of process cycle efficiency improvement to 17%, depending on various factors such as project time, project team, current process cycle efficiency and suggested improvements, although all processes reached or were already above what is considered a lean process, which is indicated at 30% of process cycle efficiency.

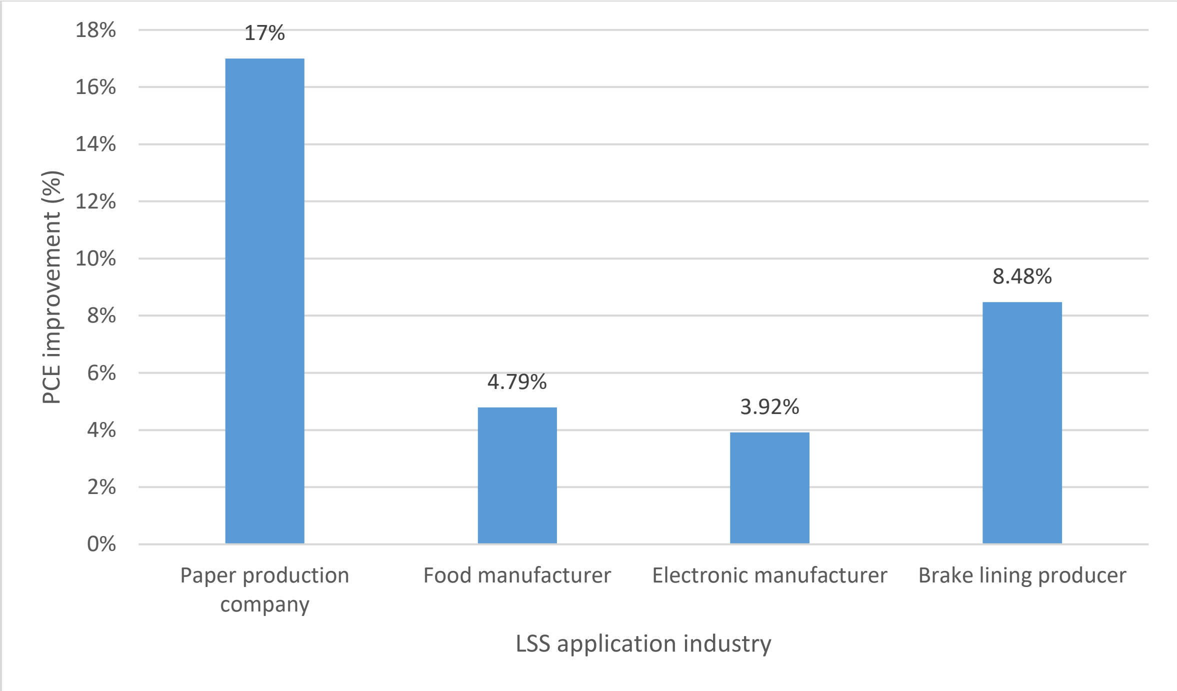

Fig. 11. Process Cycle Efficiency Improvement in Different Manufacturers

The implementation of Lean Six Sigma can also be used for defect reduction in conjunction with efficiency improvement. Moreover, the calculation of DPMO was not indicated in [20], but the improvement results were given in sigma level, where it increased from 4.07 to 4.32, indicating a quite significant increase of 0.25. Furthermore, the application of suggested improvements from LSS analysis in the food waste industry showed great results, reducing DPMO from 33500 rejected units to 2050, as it resulted in a sigma level increase from 3.33 to 4.37, which is an increase of 1.04 [22]. In addition, increasing the sigma level in a production company is a hard task, and increasing it by such a large amount is a great result, which indicates that the usage of LSS for both applications which are defect reduction and process cycle efficiency increase, provides even higher results for both outcomes [22]. Moreover, the application of DMAIC and LSS for a car parts supplier was beneficial by reducing the rejection rate of the die-casting process by 7% and the machining process by 1%, which combined increased the sigma level of those processes from 3.4 to 4 [24]. Moreover, in an Indian weather strip manufacturer, the improvements from LSS project shown the reduction of rejection from 153 pieces to 68 pieces per month, which indicated an increase of sigma level from 3.9 to 4.45, which is an increase of 0.55 and yeld significant benefits by saving 162 Euros per month [4]. In addition, improvements made in the cover coffee maker PT Mega Technology Batam did not provide any results after the analysis and improvement suggestions, leading to the fact that there are areas that need to be improved, as the current Sigma Level is very low at 3.1 [6]. The results can be seen in Fig. 12, where various DPMO improvements can be seen from 0.25 to 1.04. In conclusion, as the application of LSS varied from different researchers, the highest result was indicated from the implementation in a food manufacturer, as researchers used LSS to achieve both outcomes by reducing defects and increasing process cycle efficiency.

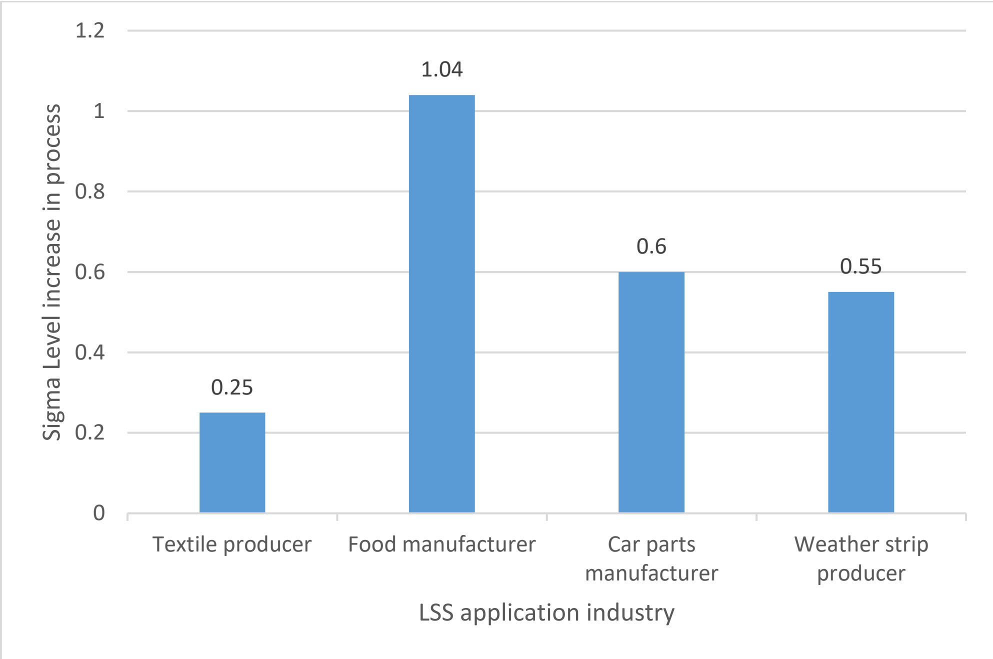

Fig. 12. Sigma Level Improvement In Different Manufacturers

2.4. Chapter Summary

The analysis of how companies and researchers use LSS methodology to improve process cycle efficiency and reduce rejection rates was done. Moreover, research methodologies that could be applied in conjunction with LSS implementation were identified to be Pareto charts, Value Stream Maps, Ishikawa diagrams, and SMED analysis. Furthermore, having good data of measurements is very important as the calculation of DPMO and PCE indicates the process stage before implementation and results after the improvements. In addition, it was noted that the highest results were yielded when the LSS was used for both outcomes, which are improvements of process efficiency and reduction of defects in the same process. Moreover, comparison of achieved results was done to indicate what kind of goal could be achieved on average by utilizing LSS in a production process, although the results vary significantly depending on the process and various other factors. Finally, it was indicated that most companies still face problems with their processes, as some process cycle efficiency ratings were below 30% while they also have an operating Sigma Level of lower than 3.5. In conclusion, Lean Six Sigma is a great tool that can be applied in various processes while also providing great results financially and socially, while also bringing sustainable practices as it reduces defects or other waste in the production.

3. Lean Six Sigma DMAIC Application in Electronic Production Process for Process Efficiency Improvement

The literature review was done to analyze the various applications of LSS in various production processes. The research showed that LSS is applicable and is still relevant in modern production facilities. Nevertheless, the high amount of application of LSS for efficiency improvement has been noted to be majorly for the manufacturers who produce products made from textile or metallic materials as there is a high cycle time amount where the main problems seem to be the inefficiencies in the changerover or process cycle as high amount of defects would be generated or a high amount of machine downtime has been measured. For further research, the experimentation will take place in an electronic product manufacturer where LSS will be applied to measure the current production process, and an analysis of the main problems will be done to find the proper solutions for efficiency improvement. Furthermore, the project will be applied by using the DMAIC cycle, where each phase will be implemented to structure the analysis for the process and the suggested improvement plan.

3.1. Electronic Component and Chosen Electronic Production Process Definition

The define phase is done to identify the process and set goals for the project, which would indicate that the LSS implementation was successful. Firstly, the LSS was applied in an IoT water meter production company, where the whole manufacturing process goes from the manufacturing of electronics, molding the housing, assembly, to packaging. The product is made almost from raw materials, as the only sub-assembly that arrived from the suppliers is the bare printed circuit boards, which need to go through the electronic assembly process to have a proper functional electronic device. In addition, as the production has a high amount of processing, the main part that was chosen for LSS was the electronic assembly process. Furthermore, to have a proper understanding of the electronic assembly process, a process flowchart was made, where each step of the production was indicated. The main objective was indicated to be process efficiency improvement by doing LSS analysis and implementing Lean tools in the production where there is an adamant of new technology being used but not fully utilized to achieve higher efficiency. The part that is produced from the electronic manufacturing process is shown in Fig. 13. The product consists of the main printed circuit board, soldered subcomponents, screen, and soldered batteries.

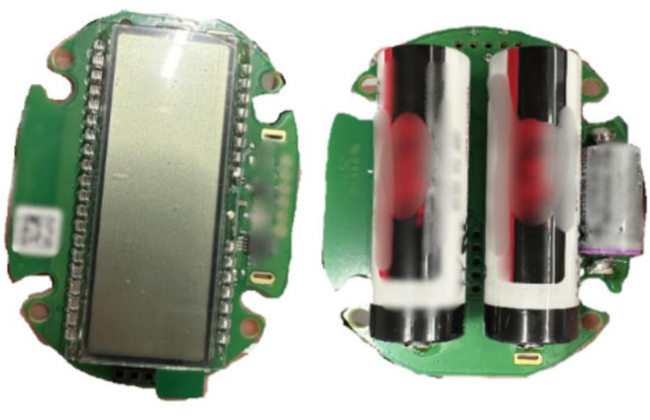

Fig. 13. Finished Part in the Electronic Production Line

The electronic assembly process consists of SMT soldering, automatic optical inspection, selective soldering for additional components, ERSA supplying, varnishing the pcb’s, after which there is depaneling and PCB testing, while the process ends with battery soldering and then scanning each PCB into the system. To have a proper workflow of this process, a flowchart was made, which can be seen in Fig. 14, which is the first part of Appendix 1. Firstly, the bare PCBs are placed in the automatic SMT line where soldering paste is applied to the surface for the further soldering process. Furthermore, after the paste has been applied, the PCBs are visually inspected, and if there are defects, they are put in the rework drawer and if there are no defects after visual inspection, the components are picked up and placed on the bare PCBs. Moreover, there is a second visual inspection done before actually soldering the components. If there is a possibility to repair the PCB by aligning the components, it is done after the visual inspection, and if there are no possibilities, the PCBs are put in the rework drawer. Furthermore, after the visual inspection, the components are soldered to the printed circuit board. In addition, after the components are soldered, the product goes through an Automatic Optical Inspection machine, where it also checks the quality of the soldering, and if there is a defect, the possibility for repair inspection is done by the operator by the IPC 10 standard. Nevertheless, if the repair could be done, it would be done by the same operator who analyzed the possibility of the repair. If the repair is not possible, the product is noted as defective and is put in the quarantine drawer, while non-defective products are placed in the drawer for further assembly. As a result, this is the first part of the soldering process where small components are soldered and visually inspected before applying other, larger components.

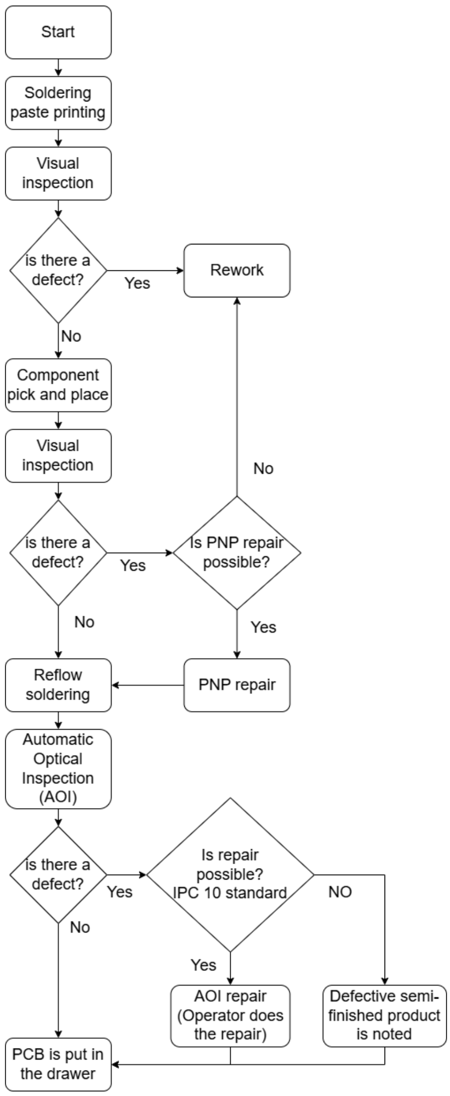

Fig. 14. First Part of the Electronic Part Assembly Process

After PCBs go through the AOI operation, the PCB surfaces are varnished in an automated line. Moreover, if the PCBs have any defects, they are checked by the operator to see if the repairs can be done before drying the circuit boards in the varnishing operation. Furthermore, if the repairs are not possible, they are still put in for drying, after which the product is again evaluated to see if there are defects. In addition, if there are any defects after drying the PCBs, the product goes through the varnishing process again. The varnishing part of the process could be seen in Fig. 15, which is the second part of Appendix 1.

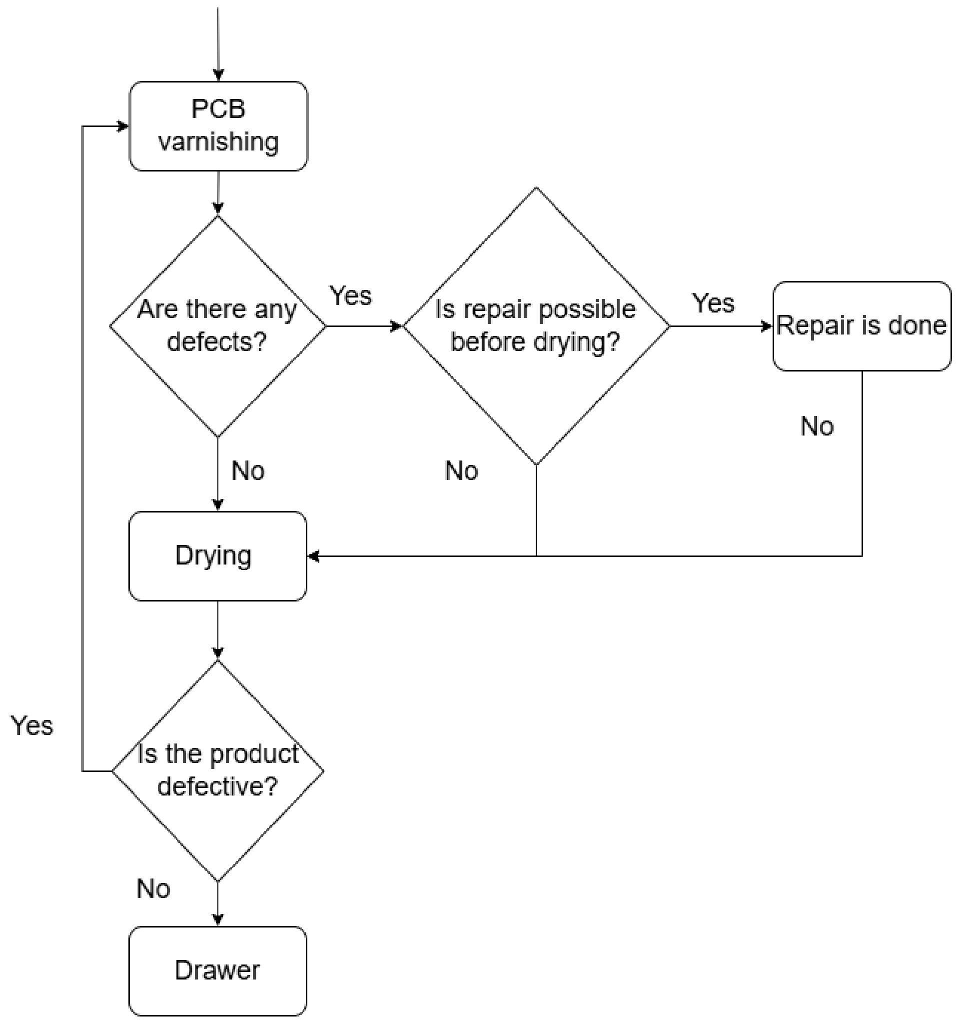

Fig. 15. Second Part of the Electronic Part Assembly Process

After the varnishing process, semi-assembled circuit boards go through another soldering process, in which larger components are added to achieve a working electronic component for the water metering device. Therefore, after the PCBs are put in the drawer, an ERSA selective soldering operator takes the product for the selective soldering process, after which the product is visually inspected if there are any defects. If the product is defective, it is marked as a defective part and is put in the quarantine zone drawer. The quarantine zone drawer is used to track the number of defects. If it goes higher than the indicated limit, the ERSA selective soldering line is stopped to evaluate the causes of the defects. Furthermore, if there are no defects repeated selective soldering process is needed to attach another component, which could be the antenna or battery connectors on the printed circuit board. After repeated selective soldering, the PCBs are put in an automatic depaneling machine where each board is milled from the holder. As a result, another quality inspection by the operator is done to evaluate if there are any defects. If there are defects, the product is put in the same quarantine zone drawer; if there are no defects noted, the product is put in the drawer from which later operations are done in production. The third part of the electronic assembly process can be seen in Fig. 16, as it is the third part of Appendix 1.

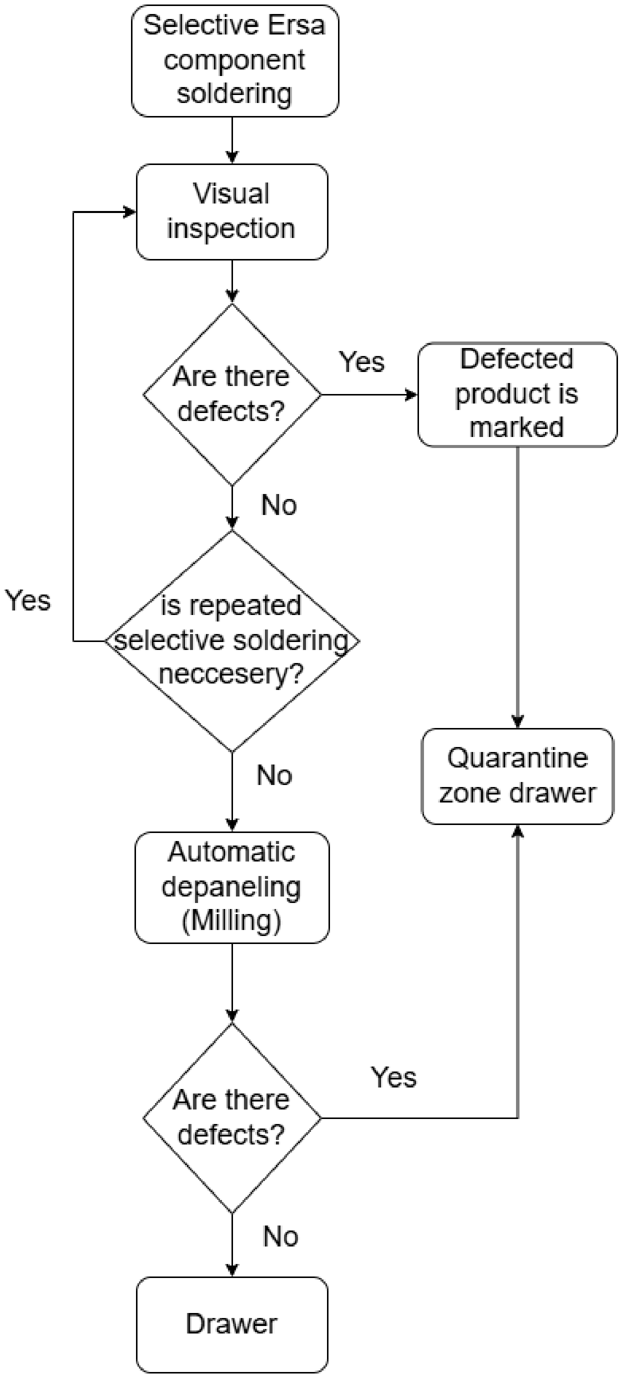

Fig. 16. Third Part of the Electronic Part Assembly Process

The third part of the electronic assembly process starts with the automatic testing of the circuit board. Furthermore, automatic testing consists of checking the circuit board by doing short circuit tests, PCB connection verification, programming the firmware to the PCB, optical communication verification, radio connection verification, flash memory verification, Near Field Communication (NFC) verification, LCD performance check, and sleep current measurement. If any of the test results from the verification process is failed, the product is marked and put in the quarantine zone drawer for the same reason as the defects from previous quality inspections. Nevertheless, if the circuit board has no defects, it is put in the drawers for the battery soldering process. Moreover, the battery soldering operation is done semi-automatically, where machines solder the batteries to the circuit board, although some input from the operator is needed as the placement of batteries needs precise placement, which cannot be done by the battery soldering machine. After batteries are soldered, a visual inspection is done to identify any defects. If there are defects that cannot be repaired, the part is marked and is also put in the quarantine zone drawer. Furthermore, fully assembled PCBs are scanned by the operator who has done the soldering for full traceability of the product throughout the electronic assembly line. After every circuit board is scanned, they are put in the drawer from which the full assembly process is done. The fourth part of the electronics assembly process could be seen in Fig. 17, as it is the last part of Appendix 1. In addition, analyzing the whole electronic assembly process is inefficient, but by creating the whole flowchart for this process, the process could be understood, and measurements could be made to find problems in this process.

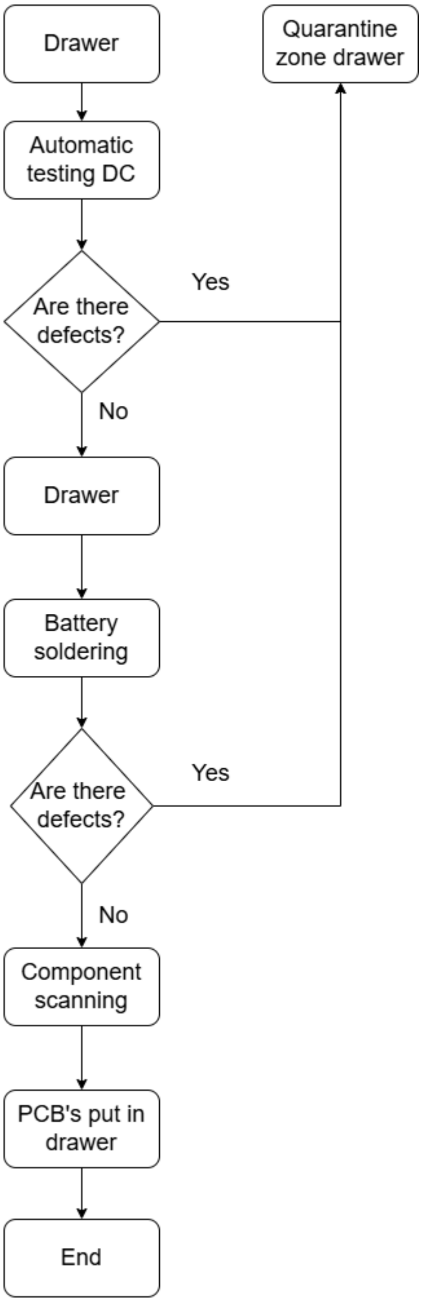

Fig. 17. Third Part of the Electronic Part Assembly Process

3.2. Electronic Part Manufacturing Process Measurement Through Value Stream Map

The measurement phase of LSS application in the assembly process is essential to ensure that the root cause of the problem of inefficiency can be found. Nevertheless, a Value Stream Map (VSM) was made to identify the current process cycle times and evaluate the whole process lead time from the ordering to the finished part reaching the assembly process. SMT soldering changeover times have been evaluated to be 15 minutes, while the cycle time for one circuit board was evaluated to be 6s. Moreover, Automated Optical Inspection (AOI) was identified to have a changeover time of 15 minutes, while the cycle time takes 6 seconds for one circuit board. Furthermore, varnishing the PCBs has been noted to have a cycle time of 4s while the changeover time is recorded to be 5 minutes. However, the selective soldering operation has a cycle time of 20 seconds, while the changeover time has been recorded to be 20 minutes. After the varnishing, the depaneling has a cycle time of 4s while the changeover time is estimated at 15 minutes. Moreover, automatic testing has a cycle time of 10s while the changeover time was indicated to be 5 minutes, because the changeover process is mainly done on the integrated computer in the automated testing operation. Battery soldering cycle time has been indicated to be at 25s, while changeover time seems to reach 5 minutes. Consequently, the scanning operation cycle time is indicated to be 12s per one circuit board while having a changeover time of 5 minutes, which is usually also done by setting up computer settings for logging in and turning on the scanner. The total value-added time is evaluated to be 87 seconds, while the total changeover time is 6300 seconds, which shows that there is a high amount of non-value-adding time in the production by having long changeover times, considering the cycle time. The value stream map could be seen in Fig. 19. The total process cycle efficiency has been calculated to be at 0.093%, which is strongly lower than a lean process cycle time should be, which is at 30% or higher.

To find issues in the production process a pareto chart is made for further analysis. Pareto chart is a great tool to not only find the root-causes of defect generation in certain processes, but it can also be used to identify and wager what process could be analyzed in the further investigation for process cycle improvement. In addition, the created Pareto chart is shown on Fig. 18.

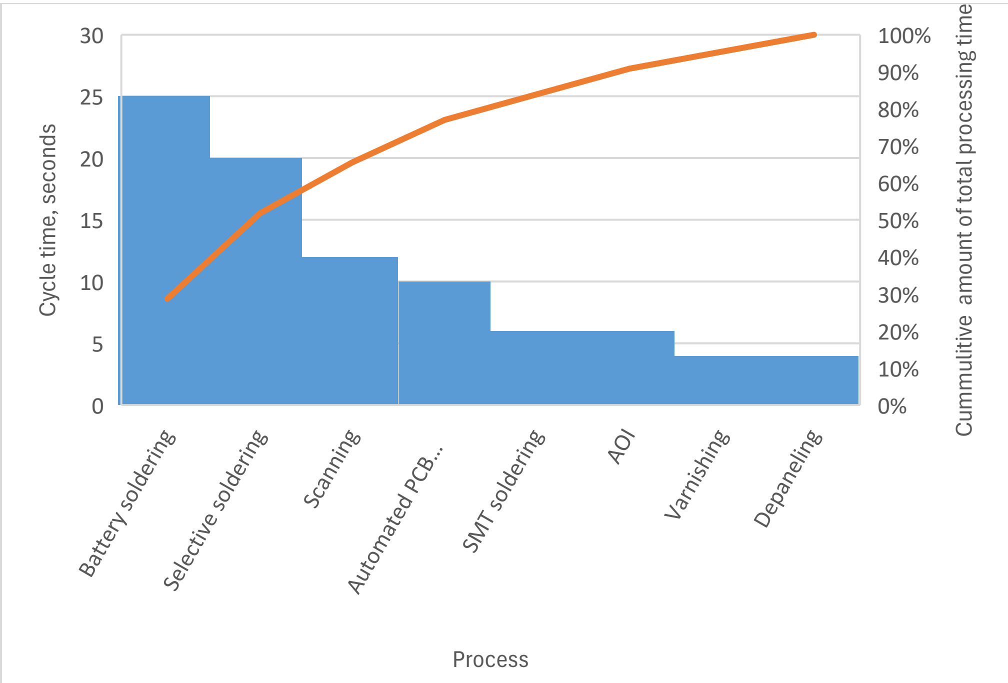

Fig. 18. Pareto Chart of Cycle Times in Electronic Part Production Process

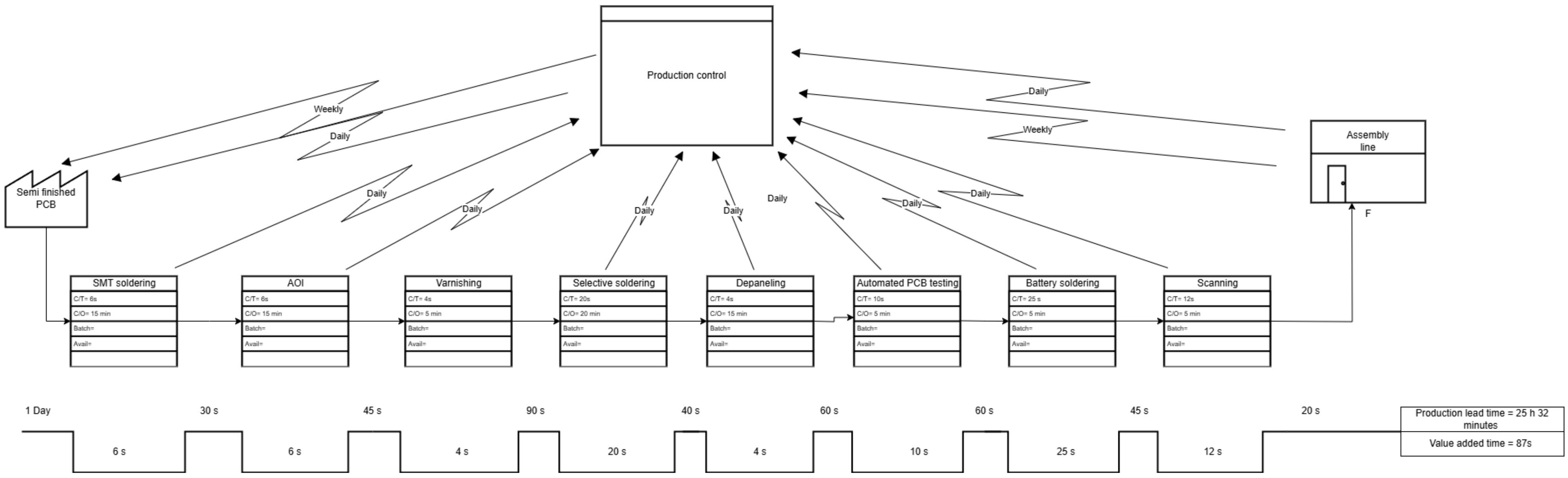

Fig. 19. Value Stream Map for Electronic Part Production Process

As a result, it is noted that the highest cycle time of 25 seconds is indicated in the battery soldering operation, which is 28.73% of the total processing time in production. Moreover, selective soldering was indicated to be second second-highest cycle time operation in production with 22.98% of total cycle time. Furthermore, the third longest cycle having operation was identified as scanning at the end of the process with 13.79%. As a result, these three operations consume 65.5% of the total production processing time. Although, the selective soldering operation is mainly automated with new selective soldering technology the improvements for cycle time are out of the scope for this project, therefore battery soldering operation is selected as the operation is only semi-automated and by applying lean and quality control tools to analyze the current process, improvements to the process cycle time and efficiency should be possible, which would bring great financial benefit to the company by increasing output of the production.

By creating a VSM and measuring each production operation cycle time, changeover time, and transportation time for each operation, the main measurements were recorded for further analysis of the process. Although most Pareto chart applications in the literature review were done through the analysis phase of the DMAIC cycle, for current process measurements Pareto Chart was designated to identify the highest cycle time causing activities in the production process. As a result, the Analysis phase of the DMAIC cycle will mainly focus on the battery soldering operation.

3.3. Analysis of Automated Soldering Process for Efficiency Improvements

To evaluate the cycle time from the soldering process, all activities of the process were timed, and a flowchart was made. The first activity of the cycle is placing the circuit boards in a holder. Moreover, the second activity is placing the supercapacitor batteries on the circuit board. Furthermore, the third activity is putting the AA batteries in the circuit board. After the supercapacitors and batteries are placed in the printed circuit boards, an upper clamp holder is placed to keep the circuit boards in place during the automated battery soldering process. In addition, the holder has a capacity to hold 12 circuit boards at a time, as the automated battery soldering station is calibrated to solder 12 circuit boards. After the circuit board is held in place by the added clamp holders from the top, already soldered batteries are taken out from the soldering station, and the unsoldered batteries at put in place, and the automated soldering operation is launched. While the automated soldering operation is in automated soldering mode, the newly soldered batteries are visually inspected for any soldering defects. Moreover, if there are any soldering defects are noticed on the printed circuit board, rework is manually done by the operator. After the finished products are inspected, the circuit boards are individually put in trays, which can hold up to 16 units. While the automated soldering process is continuously soldering current batches, the operator prepares a new batch of circuit boards for the automated robot, thus starting the cycle again. In addition, there are two soldering stations for one operator, as both are active while the operator technician is always preparing the next batch. In addition, before each new batch, the operator evaluates if there are enough components for the next batch, as the current holders do not have enough space needed to hold all the components for one shift, causing the operator to leave the battery soldering workplace to gather required components, increasing cycle time. Although the need for material replenishment is not that frequent, therefore the need for collection is not that frequent, although elimination of this step would bring great benefit for process efficiency. Furthermore, to properly assess the battery soldering operation, a flowchart was made, which is shown in Fig. 18. After defining the battery soldering process, the monitoring of each activity time could be made for further investigation.

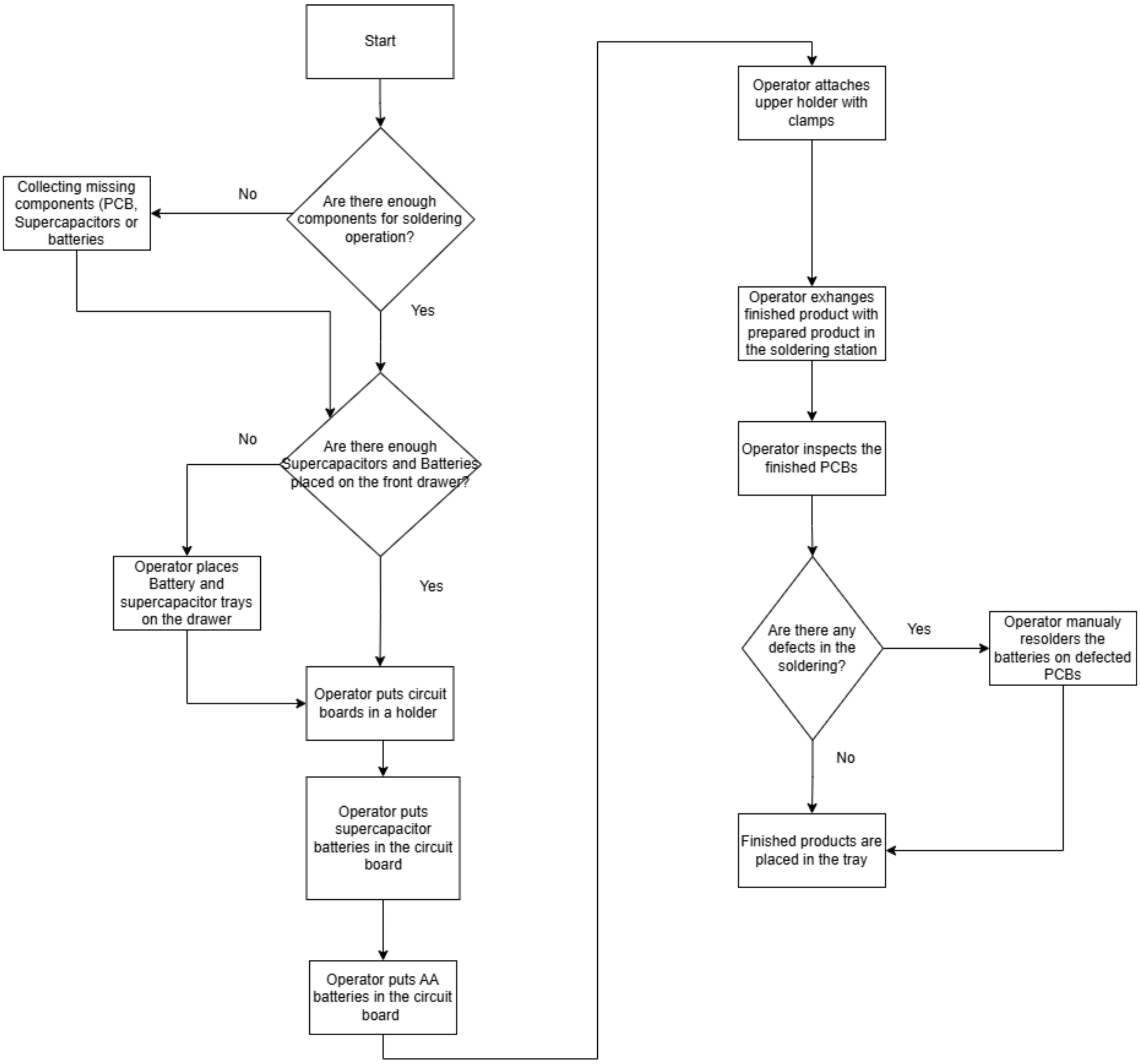

Fig. 20. Battery Soldering Operation Flowchart

The cycle time has been evaluated and monitored to capture the times of how long each activity lasts. The calculated activity times are shown in Table 1. in which all the automated battery process activities were divided into value adding nonvalue adding activities.

Table 1. Automated Battery Process Activities

Activity description	**Time**	**Activity type**
Collecting missing components	5 s	Non- value- added activity
Putting supercapacitors and PCBs on a slanted drawer in front of the workplace	12 s	Non – value – added activity
Putting PCBs in the holder	22 s	Value-added-activity
Putting supercapacitors in the PCB	52 s	Value-added-activity
Putting batteries in the PCB	55 s	Value-added-activity
Putting upper clamp holder	13 s	Value-added-activity

Activity description	Time	Activity type
Exchanging the finished PCBs with the prepared PCBs on the soldering station	15 s	Value-added-activity
Visual Inspection of the current PCB and putting finished products in the tray	60 s	Non-value-added activity
Resoldering defective PCBs and putting them in the tray	60 s	Non- value-added activity
Total activity time	294 s	

As seen in Table 1, the total cycle time was evaluated to be 294 seconds. Moreover, value-added activities were identified to be the PCB placement in the holder, supercapacitor placement in PCB, battery placement in the PCB, placing the upper clam holder on the batteries, and exchanging PCBs with batteries with new prepared PCBs in the soldering station. Furthermore, non-value-added activities were identified to be the collection of missing components, putting supercapacitor and battery trays on the drawer in front of the workstation, inspection of the current PCBs, resoldering batteries on the defective circuit boards, and putting finished products in a tray. As a result of the activity measurements, the most time-consuming activity comes from resoldering the defective circuit boards, as the automated stand creates defects during the soldering operation and the collection of materials, which will be used in the assembly process. Moreover, the resoldering of defective units could be evaluated up to 60 seconds, while the robots are calibrated to finish a batch in 360 seconds. Moreover, the collection of missing components was calculated by dividing the finished cycles during one shift by the whole time taken to pick up the components, as during the whole shift, the need for replenishment takes up to five times. Furthermore, defective soldering leads to inefficiently utilized automated soldering robot cycle time, as delays create waiting time for the robots, thus leading to non-value-added activity. Therefore, the main problem has been identified as defects generated by the automated soldering station for the cycle time, as the collection of materials is done rarely. The generated defect could be seen on Fig. 21.

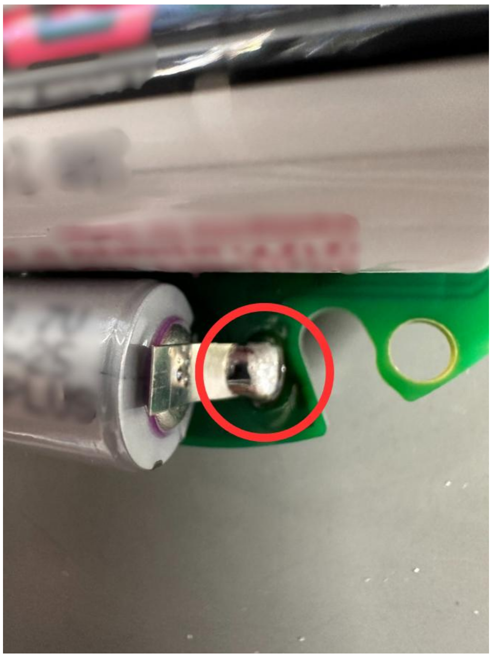

Fig. 21. Soldering Defect on the Printed Circuit Board

For deeper analysis of causes which could affect the defect generation from the automated soldering machine a fishbone diagram was created. Moreover, the fishbone diagram has been created with five areas where the root cause of the soldering defect may appear. The Ishikawa diagram can be seen on Fig. 22.

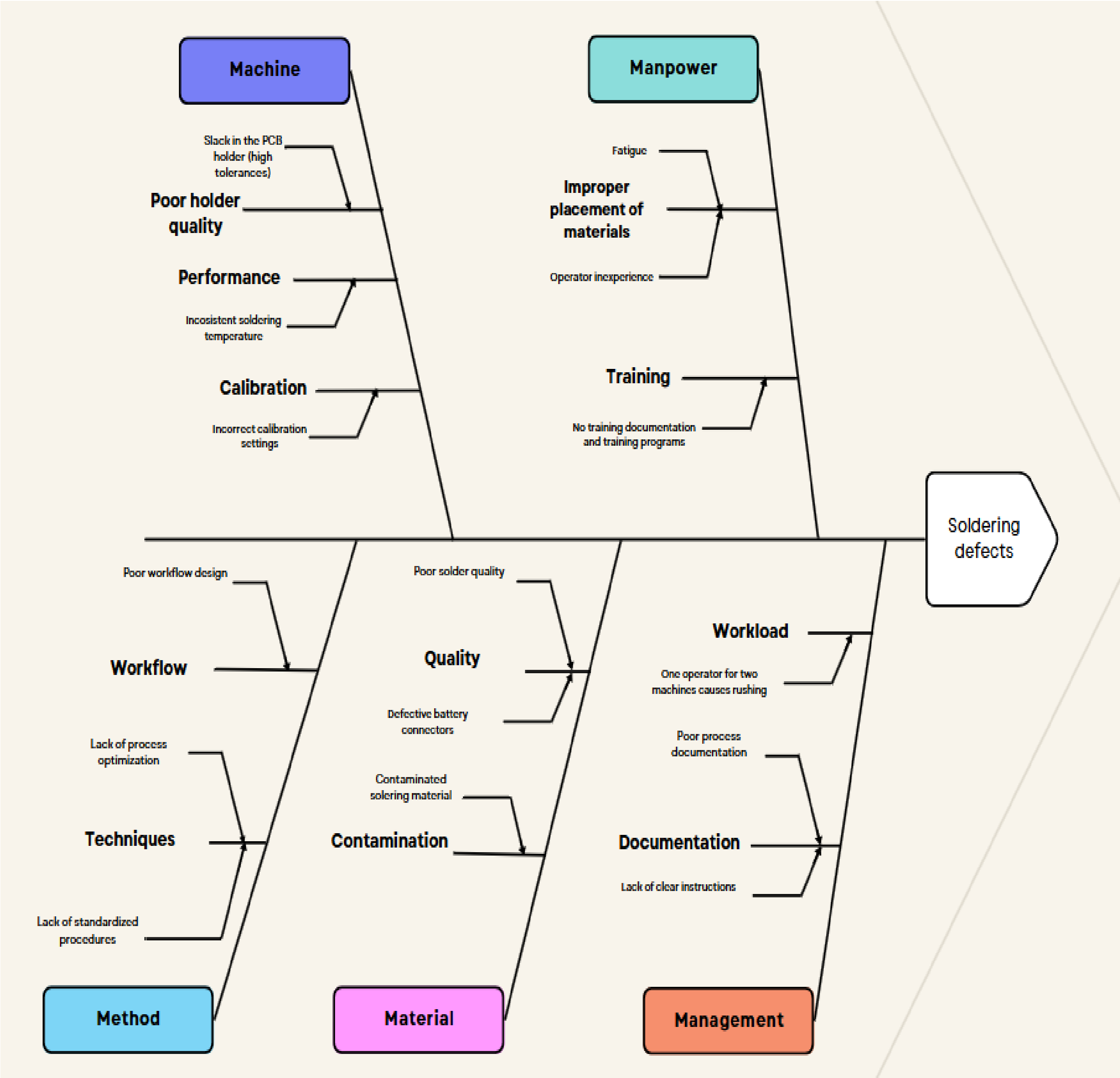

Fig. 22. Fishbone Diagram for Soldering Defects in Automated Soldering Process

Furthermore, the five areas of causes have been identified to be manpower, machine, method, material, and management. Moreover, evaluating the causes of manpower, it was identified that there could be issues of how the batteries are placed in the printed circuit boards, which could be caused by operator inexperience or fatigue throughout the whole shift. The improper placement could cause the soldering material to not go through the whole board, causing the need for resoldering the batteries manually to the circuit board. Furthermore, the lack of training and no operation documentation can also be the cause of the soldering defects, as it can also be related to improper placement of the batteries of the PCB holder itself onto the soldering machine. Although creating a Ishikawa diagram for machine area of defect causes, it was elevated that a poor-quality material used for the holder could be a problem for improper soldering defects as there might be slack and movement when the PCBs are placed in the holder as it might have too high of a tolerance or needs to be replaced. Another problem that could be the cause might be the improper soldering temperature as the temperature is inconsistent, and sometimes the solder does not fully through the hole of the circuit board where the battery is placed. Consideration of incorrect calibration settings was evaluated if the defects that are generated are usually at the same holder spot, which means the machine might be incorrectly calibrated at the set point. Consideration of the method was designed to evaluate whether there might be problems with current placement techniques, as there is no standardization for the process. Moreover, workflow could be poorly designed as sometimes the operator needs to walk to get batteries or printer circuit boards, breaking the cycle, which could also cause incorrect placement of the batteries. Furthermore, in the material area from which the root cause could be generated, it was evaluated that the quality of the solder could be improper, leading to the defects. In addition to having poor solder quality, an assumption could be made that battery connectors might also be of improper quality, leading to variability and inaccuracy of the automated soldering machine, which causes the solder to not go through the whole PCB.

Although if the solder quality is good and should work properly, another issue that could be causing the defects is contamination of the soldering material. If the soldering material is not properly warehoused, it could lead to contamination, which could affect the quality and reliability of the solder joints. Furthermore, the contamination of solder material could be oxidized from the moisture in the air, therefore creating weak soldering joints and poor wetting. Moreover, dirt, dust, or even oil could contaminate the soldering material, especially if the soldering material is in contact with hands and other tools that were not cleaned properly, this contamination could affect the solder flow and create unreliable connections. There are various causes of the contamination, but analyzing the company process, none of them should be applicable. In addition to these four areas the management area was created to evaluate the root cause from the management perspective as mentioned before there are lack of clear instruction and documentation of the automated battery soldering operation, moreover the workload seems to be heavy, there is no room to breathe as the whole process cycle is very repetitive which could lead to early fatigue for the employees. The main root causes of the generated defects were concluded to be the poor quality of soldering material or contamination of the soldering material, improper placement of batteries in the PCBs, and calibration or maintenance problems for the automated soldering machine, creating inconsistent soldering temperatures.

To find the origin of the problems, 5 whys were used for the main problems found to identify the true root cause. Moreover, the 5 Whys is a great tool for the analysis phase, as finding the main issue could lead to proper solution suggestions. Furthermore, 5 why’s were applied to the causes of defective battery soldering on the automated station and are shown in Fig. 23. Firstly, the contaminated solder material was analyzed by asking why the solder is not flowing through the PCB hole where the battery connector is, which the answer of improper wetting throught the hole was assumed. Moreover, the question of why the wet solder does not flow through the hole was asked, which created an answer to the soldering material being contaminated or oxidized. Furthermore, the cause of contamination and oxidation was assumed to be exposure to dust, moisture, or mixing with other materials that are not compatible with each other. In addition, the exposure to the environmental causes could be because of improper storage of the soldering material, as the solder spools could be kept open or in unsealed containers. As a result, the solder material warehousing has no standardized material handling procedure, causing defects in the automated line.

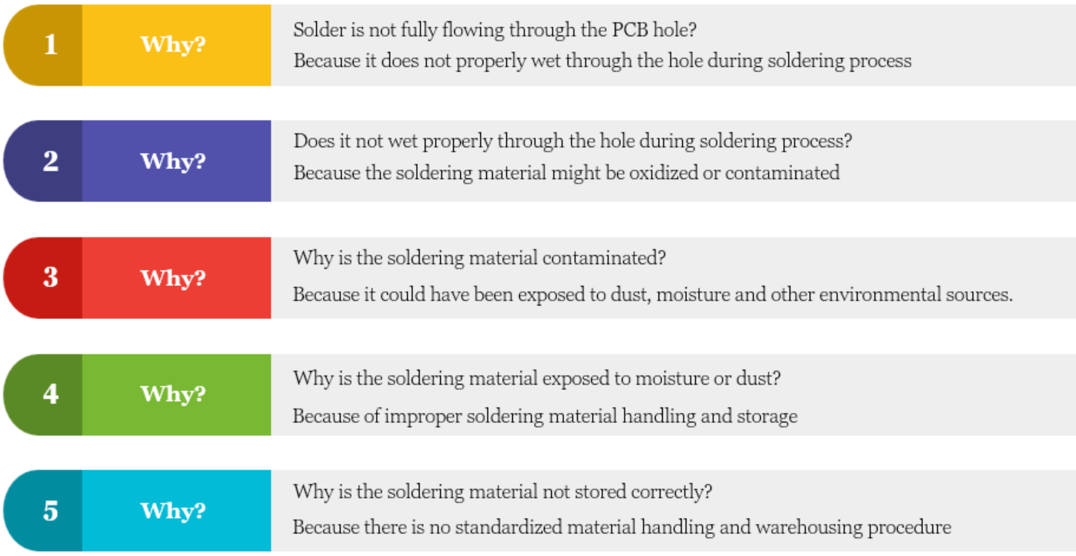

Fig. 23. 5 Why's Method for the Contaminated Solder Material

Poor soldering material quality might be the root cause of the defects caused by the automated soldering station. Moreover, 5 whys were used to deduce the root cause of the poor soldering material, which could be seen in Fig. 24. Firstly, the reason for bad solder flow was indicated to be improper melting and flow of the solder material through the PCB. Secondly, the reason for the bad melting was indicated to be a bad composition of the solder alloy. Moreover, the improper solder material composition indicated that the supplier provides low-grade solder, or there might also be inconsistencies in the manufactured batches. Furthermore, the inconsistencies in the manufacturing are not noticed because no quality checks are done before the automated soldering operation, where solder testing should be necessary, and no assumption should be made that the material already complies with the standard without any verification.

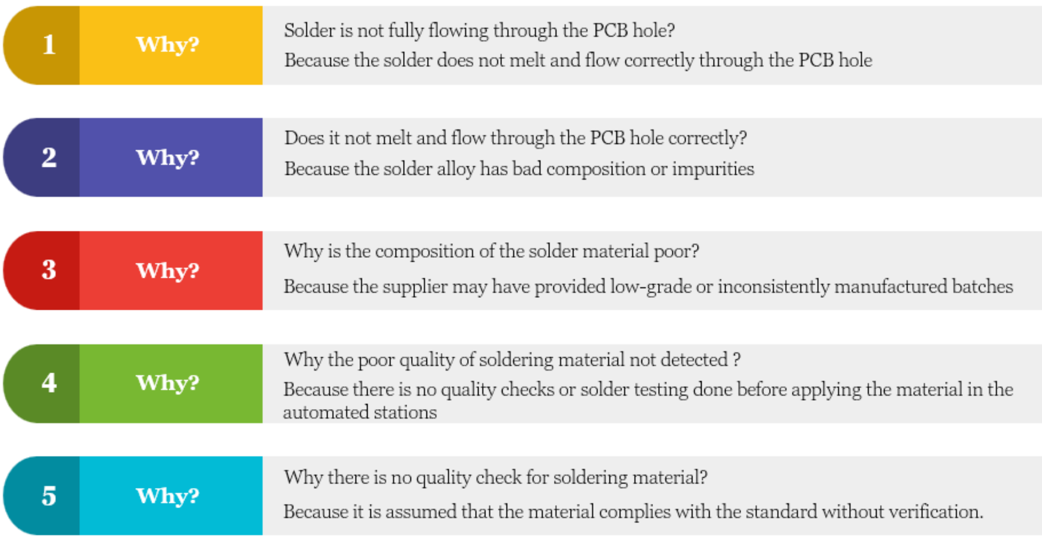

Fig. 24. 5 Why's Method for Poor Soldering Material Quality

The third main cause of the generated defect is noted to be improper calibration of the soldering machine. In addition to the noted cause, 5 whys were also used to identify why this could be the problem. The 5 whys for improper calibration of soldering machines can be seen in Fig. 25.

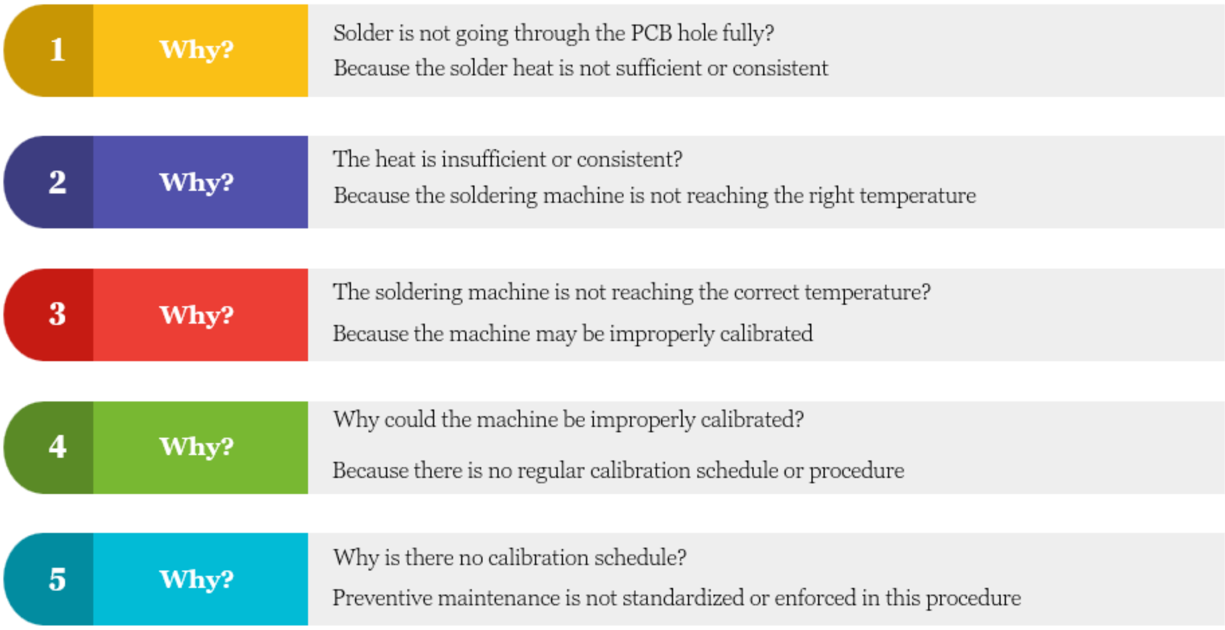

Fig. 25. 5 Why's Method for Improper Machine Calibration

Firstly, it was implied that the solder heat might not be consistent or sufficient for the current material. Moreover, it was noted that because of inconsistent temperatures, the machine might not be properly calibrated. Furthermore, the issues with the not properly calibrated machine might come from no scheduled maintenance procedures implemented in the company for the automated soldering station. Nevertheless, the main root cause was found to be that there are no preventive maintenance procedures in the company for the automated soldering station, which should be standardized and repeatedly implemented according to a certain schedule. Finally, the main root causes were found by implementing 5 whys, which are directly related to soldering material quality, warehousing of the soldering material, and calibration of the machine. The root causes that were found were that there are no quality checks and inspections done to the solder material, which comes from the supplier, there is no standardized solder material handling and warehousing procedure implemented in the company, and there are no preventive maintenance practices implemented for the automated solder machine maintenance and calibration.

After the cycle time for the automated battery soldering station was analyzed and root causes for defect generation were found, improvements for the setup/changeover process in the battery soldering station should be made for complete cycle efficiency improvement. Firstly, the set-up process activities were analyzed by creating a flowchart of the current set-up process. As seen in Fig. 26, the process starts with the operator manually gathering the required materials at the soldering station. As the PCBs without batteries are gathered and placed near the workstation, the same is done for supercapacitor batteries and AA batteries. This manual gathering of materials takes up 88 seconds. Furthermore, later steps consist of starting the computer, logging into the account, and starting the automated robot application in the computer environment, which takes up 160 seconds. After the automated robot applications have started, the operator turns on both automated soldering robots by pressing physical START buttons, which take up 20 seconds. Finally, the operator places battery and supercapacitor trays on the slanted drawer, which is in front of the workstation for easy access while assembling batteries to the PCBs, this action takes up 12 seconds. Leading to the total setup time of 280 seconds.

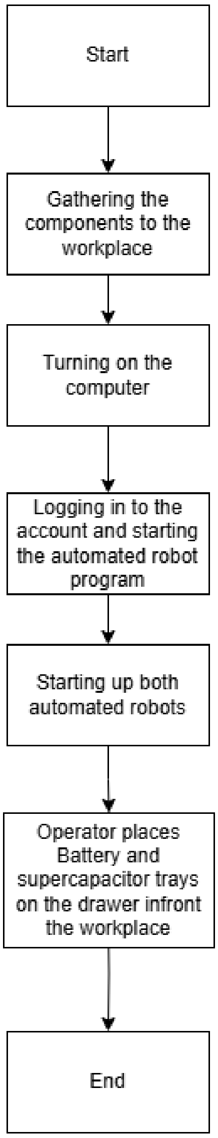

Fig. 26. Set-up Process for Automated Battery Soldering Station

For further analysis, the measurements of the setup operation have been analyzed for process improvement. Moreover, all the set-up processes are considered non-value-added activities as the whole operation does not add any value to the customer, even if the process is necessary to produce finished printed circuit boards. Firstly, a spaghetti diagram for operator movement in the setup process has been made, where the highest amount of walking is done for the component gathering in the first step of the setup process. The spaghetti diagram could have been in Fig. 27, as firstly the operator goes to collect the supercapacitor batteries and goes back to the cart near the operator workstation to place them, later the operator does the same for PCBs and AA batteries. Moreover, at the current process, the operator seems not to use the mobility of the cart as it cannot hold more than 8 trays for each component, while also having a place to put already finished PCBs. The root cause of the current problems with the setup seems to be excessive transportation times, where improvements could be made in the improvement stage of the DMAIC cycle. Although there is a higher non-value adding activity, which is setting everything up in the computerized environment, after analysis of the procedure, no areas for improvement were found there.

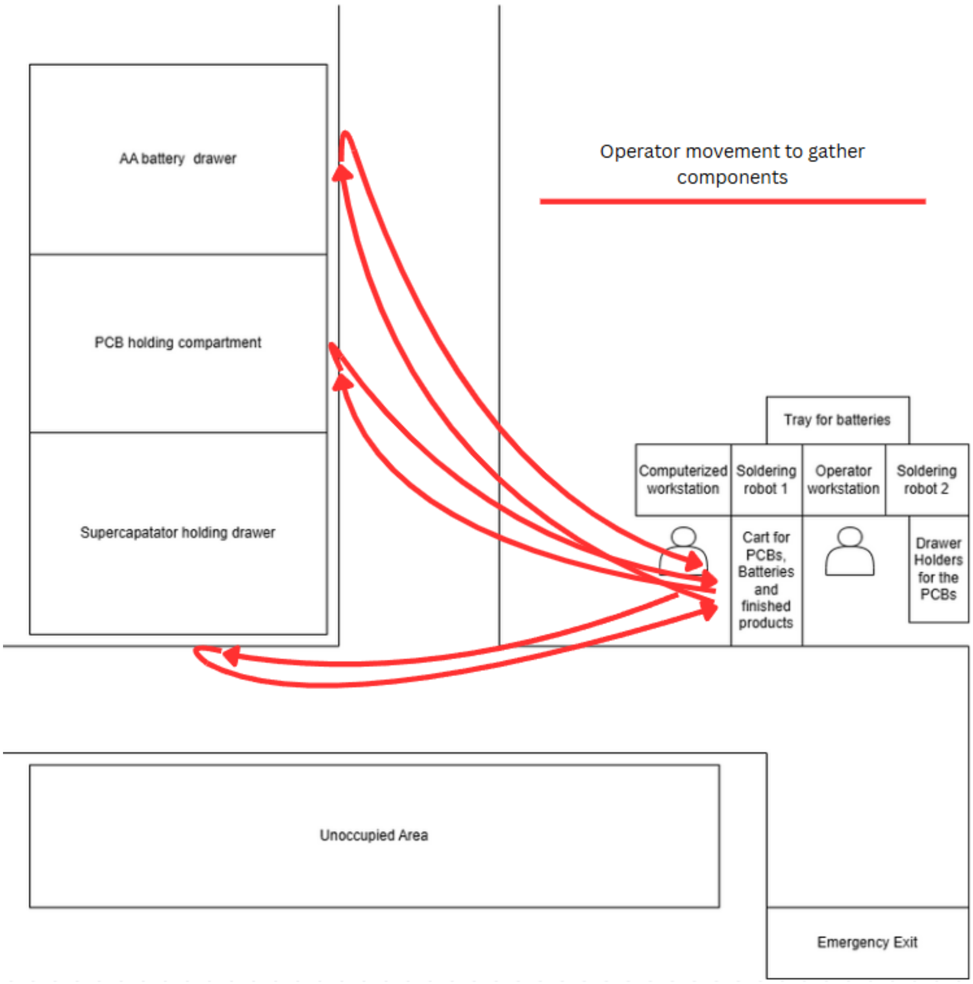

Fig. 27. Spaghetti Diagram for Operator Walking in the Component Gathering Step of the Set-up Process.

After analyzing the process by creating a flowchart and addressing the long time for collecting materials for the assembly total set up time can be calculated. Moreover, the total setup time with all activity times could be seen in Table 2. Moreover, the total setup time has been evaluated to be 280, and improvements could be made by reducing the walking distance for the component gathering step.

Table 2. Set up Process Activities and Time

Activity	**Time**
Gathering components for the workplace	88 s
Turning on the computer	10 s
Logging in to the account and turning on HORA and the automated robot program	150 s
Starting up both automated robots	20 s
Putting supercapacitors and PCBs on a slanted drawer in front of the workstation	12 s
Total time	280 s

3.4. Suggested Improvements for Automated Soldering Process

After successfully identifying the root causes of the defects generated in the automated soldering station, suggestions could be made to improve the process cycle time. Firstly, the current soldering material is not suitable for the automated soldering station; therefore, a suggestion to change the material to a high-quality lead-free solder alloy is necessary to ensure a good flow throughout the PCB hole. The suggested solder material is Ersa SAC305, which follows the industry RoHS standard, as in the EU regulation, where there is no lead in the solder material composition. The solder composition consists of 96.5% of SN, 3% of AG, and 0.5% of CU. The melting point of the Ersa SAC305 has been mentioned to be at 217°C, which should be in to consideration when the automated soldering robot is calibrated to achieve the great wetting characteristics that this solder has, moreover the supply is with clean flux core and fits in to IPC J-STD-004 clasification for fluxes of high quality solder interconnection as this standard is used for quality control in the manufacturing processes of soldering materials, so when purschasing the solder material this classification should be taken in to consideration. Moreover, the storage of this soldering material should be done in sealed and anti-static containers in an area in the warehouse where it is dry, and the container is temperature controlled to prevent oxidation as the humidity in the cabinet should be lower than 10% and the soldering material should only be handled by trained personnel. The recommended cabinet for storage would be Totech XSDC 601-01 to maintain the temperature between 0 °C and 12 °C, with an efficient amount of storage volume, which is 466 liters.

To ensure the quality of the supplier, a quality check should be done in the warehouse quality control procedure. The quality check should be done by the quality control inspector for each new batch that is delivered to the warehouse. Firstly, the process should be standardized, and instructions should be made where the first step of the inspection should be a visual check by cheking the wire quality as it should be shiny with no signs of oxidation or moisture exposure, a visual check on damage should also be done so that there is no flux leakage. The second step would be the verification of the label by the lot number, manufacturing date, and expiry date. The third step would be to do a wetting test for one of the wires from the new batch by using a copper coupon, where the expected results would be to evaluate if the solder flow is even while no balling or sticking occurs. The fourth step would be to ensure that the flux quality in the solder wire is good, as there should be no burning smell when heating. These steps should be documented by filling out the inspection log, and if the supplies fail any of the tests, the material should be placed in the quarantine drawer. The prepared checklist for Quality control can be seen in Table 3. Having a quality check procedure for soldering material allocated to automated soldering machines would eliminate any causes of soldering machine-generated defects.

The third main cause for the defective generation of the soldering machine was indicated to be a lack of maintenance and calibration procedures being done on the equipment. Therefore, a routine maintenance plan was suggested for the automated battery soldering station. Moreover, the responsibility for the maintenance procedure and following the plan is indicated by the maintenance technician. Furthermore, for the documentation, it was suggested that a maintenance logbook should be established with digital records through Excel or internal software that is used for Enterprise Resource Planning (ERP). Moreover, the maintenance plan should consist of weekly checking and completing a checklist, while monthly, there would be calibration procedures done. In addition, the weekly checklist should consist of these procedures: cleaning of the soldering tip, checking solder feeding speed and consistency, verification of the temperature settings by checking the soldering temperature with an external calibrated thermometer, and cleaning the ventilation filters. The prepared weekly maintenance plan checklist can be seen in Table 4.

Table 3. Inspection Checklist for Soldering Wire Quality Control

Material information				
Item Description	**Lot No.**	**Manufacturer**	**Expiration date**	
Solder Wire				
Inspection Checklist				
Inspection criteria		**Accepted**	**Rejected**	**Notes**
Solder wires have no visual defects from transportation		☐	☐	
The lot number, manufacturing date, and expiration date are correct		☐	☐	
Solder wires have no leakage, corrosion or oxidation		☐	☐	
Solder flow is even with no balling or sticking rises		☐	☐	
No burning smell when heating the solder wire		☐	☐	
Is the solder material accepted?		☐	☐	

For the monthly calibration procedure, there should be certain steps that need to be completed to fulfill the calibration requirements. Firstly, the soldering tip temperature should be measured by using a thermocouple probe and a thermometer, the measured temperature should be compared with the machine set temperature output, while the allowed tolerance should be ±5°C. Moreover, if the temperature settings are higher than the allowed tolerance, the calibration settings should be adjusted to eliminate the differences. As a result of the calibration procedure, a testing process should be done to check the reflow on a sample PCB to see if the soldering material fully goes through the PCB, the fillet shape is smooth, and there are no cold joints. The prepared monthly maintenance checklist can be seen in Table 5. By creating a routine maintenance plan from weekly and monthly routine maintenance activities, the machine factors for defective generation should be eliminated, which was impacting the process cycle time.

Table 4. Weekly Maintenance Plan Checklist for Automated Battery Soldering Station

No.	**Description**	**Tool / Method**	**Status**	**Notes**
1	Cleaning the soldering tip	Tip cleaner	☐	
2	Checking the solder feeding speed and consistency	Manual feed test	☐	
3	Verification of solder temperature setting	External calibrated thermometer	☐	
4	Cleaning/changing ventilation filters	Compressed air	☐	

The suggested improvements in the soldering operation should eliminate or minimize the need to manually resolder the batteries to the PCBs, ensuring the soldering material goes through the whole hole in the circuit board. Although the current process still has inefficiencies when there is a need to gather materials during the soldering operation, as not enough components are gathered during setup time in the workstation for the whole shift. Nevertheless, further analysis will be done to evaluate the set-up time for the current soldering process, where layout improvements could be made to eliminate or reduce the non-value-added activity. In conclusion, evaluating the process cycle time of the soldering operation is beneficial by implementing suggested improvements, but setup time is also essential to ensure no bottlenecks are left during the process.

Table 5. Monthly Maintenance Plan Checklist for Automated Battery Soldering Station

No.	Description	Tool / Method	Status	Notes
1	Cleaning the soldering tip	Thermocouple and calibrated meter	☐	
2	Compare the machine setting temperature to the measured temperature	Data comparison	☐	±5°C tolerance
3	Adjustment of calibration settings if a deviation exists	Software adjustment	☐	
4	Testing the solder on a sample PCB	Visual inspection	☐	Full wetting, no defects
5	Record calibration settings and results	Logbook	☐	

For the improvement of the setup process, the workstation arrangement should be improved to reduce the walking distance of the operator while gathering all the components. To improve the workstation layout, 5S implementation is suggested to standardize the current layout by setting everything in order. Therefore, to improve the workstation arrangement, the unoccupied area should be utilized, where some of the area could be allocated for the automated soldering station, as all the needed components could be placed in drawers daily by the logists. Moreover, the components placed daily in the currently unoccupied area should cover all three shifts by placing enough components that could be evaluated from the daily output of the automated soldering machine during the three shifts. As a result of this suggestion, the operator would have a reduced walking time for the setup procedure. In addition to improving walking time, a suggestion is to use labels for the tiered drawer cart to eliminate doubt and variation in how the components are picked up and placed on the cart. Therefore, a standardization is made for the component pick-up process where in the top drawer the PCB trays would be placed, the middle drawer would be used for the supercapacitors, and the bottom drawer would be used for the batteries. Moreover, to improve the layout for the operator workstation, a fixed drawer should be used on the left side of the operator where a cart is used instead. Using a fixed drawer, with more space, would increase the component holding capacity during the soldering process, eliminating the need to replenish the needed components during the soldering process, which hinders the process cycle time and efficiency as it is a non-value adding activity. After these suggestions are implemented, the setup process should see an improvement in the setup time, thus increasing the process cycle efficiency. To visually see the improvements, a spaghetti diagram is made with the layout improvements, which can be seen in Fig. 28.

An improvement stage is essential to ensure that the root causes of non-value-added activities are eliminated. Although suggestions and calculations show that the process cycle time was reduced and the setup time was improved, a control phase is necessary to keep the improvements sustainable. Therefore, in the further stage of DMAIC, documentation should be prepared for improved battery soldering and setting up processes. In conclusion, the research successfully confirmed that LSS can be applied to electronic device manufacturers, as there are still areas where improvements could be established, even though most of the production line is automated.

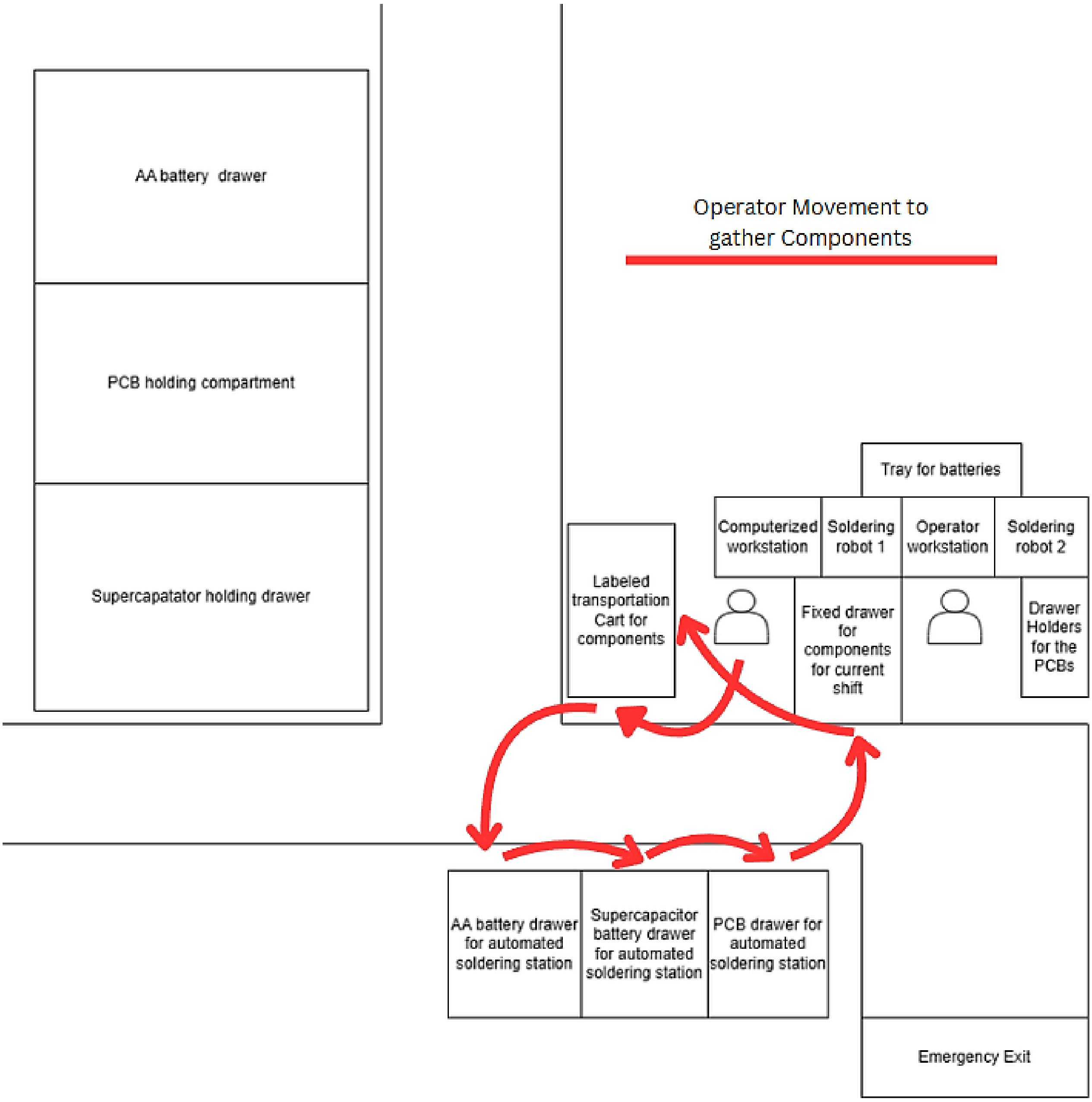

Fig. 28. Spaghetti Diagram After Layout Improvements

3.5. Control Phase of Automated Soldering Process for Improvement of Sustainability

To fully establish a correct control stage, certain goals should be defined for this phase to be successful. Firstly, the setup and cycle times need to stay reduced after the improvement phase, meaning documentation should be implemented as the new practices should be standardized, where employees related to this process are aware of the improvements and new steps in the process. Therefore, a new Standard Operating Procedure (SOP) has been created for the automated battery soldering process, which could be seen in Appendix 2. Moreover, implementation of monitoring systems should be introduced, while process cycle time is already monitored by evaluating the number of products manufactured in the automated soldering process for each shift, the setup time is not actively monitored. Therefore, a monitoring sheet for setup time is introduced containing the

Operator ID, setup start, and end time, while also having an area where issues encountered during the setup process could be written up and addressed. Furthermore, as one of the causes could have been improper employee training, training the operators and preparing them for the improved method is established by creating a training checklist where operators would periodically be re-trained to ensure all procedures are done by the documented steps. Furthermore, a buddy system program could be implemented in the automated soldering process, where the training and checking of employee knowledge of the procedure would be done by their colleagues, as cross-checking would be implemented. Furthermore, as the layout is created by taking into consideration the 5S, a visual standard document should be created for the automated soldering station, where monthly monitoring procedures would be made by including the employee who is responsible for keeping the operating station up tp 5S standard. Audits would be done by the process improvement specialists to analyze if the monthly inspections and the workplace are up to 5S standards. Moreover, it was proven [30] that 5S implementation through continuous improvement procedures would create an efficient and clean workplace by not forgetting the ergonomics, where improvements in the performance of the process could be seen. As stated in [30], utilizing the Total Production Management process with 5S, overall equipment efficiency increased from 65.59% to 68.12%. Therefore, 5S standards are essential in the current automated soldering station, as no monthly checks and quarterly audits are made.

To further improve the process in the future, Kaizen is implemented for a continuous improvement ideology in the electronic part production process. Moreover, Kaizen should be implemented by promoting interaction through issued bonuses, where meaningful and actual improvement ideas would be incentivized by providing the employee with a bonus after successful improvement implementation. Moreover, as mentioned in [29] Kaizen is following the principle of "2-6-2" rule where two of ten employees would be very posivite and continuously provide suggestion, while six out of ten people would would be indifferent as they would not provide suggestions although they are susceptible to approving the new ideas of improvement, while last two out of ten are negative shutting down new ideas and are unsusceptible to any changes in thei work. Therefore, to improve these measures, an award system is implemented, where credit is given for each suggestion submitted, and if the suggestion is approved and implemented, a 200 EU bonus will be provided for the employee. As a result, the employee engagement for continuously providing improvements should increase, which would benefit the company more as the processes are further improved. In conclusion, Kaizen is essential to ensure that the current process is not only sustained but also continuously evaluated and improved by any employee of the company.

3.6. Chapter Summary

DMAIC methodology was implemented in the electronic part production process of a water metering device manufacturer. Quality control tools such as spaghetti diagrams, Ishikawa diagrams, flowcharts, and Value Stream Maps were used to find the root causes of inefficiency in the automated soldering process. Improvement suggestions were provided to eliminate or minimize the root cause, thus increasing the efficiency of the battery soldering process. Furthermore, control and monitoring practices were suggested to sustain the improvements made in the process by implementing Lean methodologies and tools such as 5S and Kaizen. Therefore, LSS applications in an electronic product manufacturing process have been evaluated to be successful as every stage of DMAIC was applied successfully.

4. Financial and Social Benefits of LSS DMAIC Application in The Automated Soldering Process

The results from Lean Six Sigma methodology application in the production process should ensure that the company is financially and socially satisfied with the outcome of the analysis and the improvements made. By eliminating or reducing non-value-added activities in production processes, cycle time is affected positively, as more products can be made in the same amount of time. Before the LSS application, the setup time was evaluated to be 280 seconds, while the process cycle time at 294 seconds, which indicated a bottleneck in the electronic production process, as the highest cycle time was indicated in the automated battery soldering process. After the implementation of the suggested improvements, the cycle time is reduced to 232 seconds by eliminating the solder defect generation, resulting in 60 seconds of time saved for rework operation and reducing 2 seconds for gathering the materials during the cycle time for the whole shift of 7 hours. Setup time is reduced to 247 seconds by eliminating walking time at the start of the setup, which saves 33 seconds. Moreover, the comparison of reduced process cycle time before and after Lean Six Sigma DMAIC application can be seen in Fig. 29.

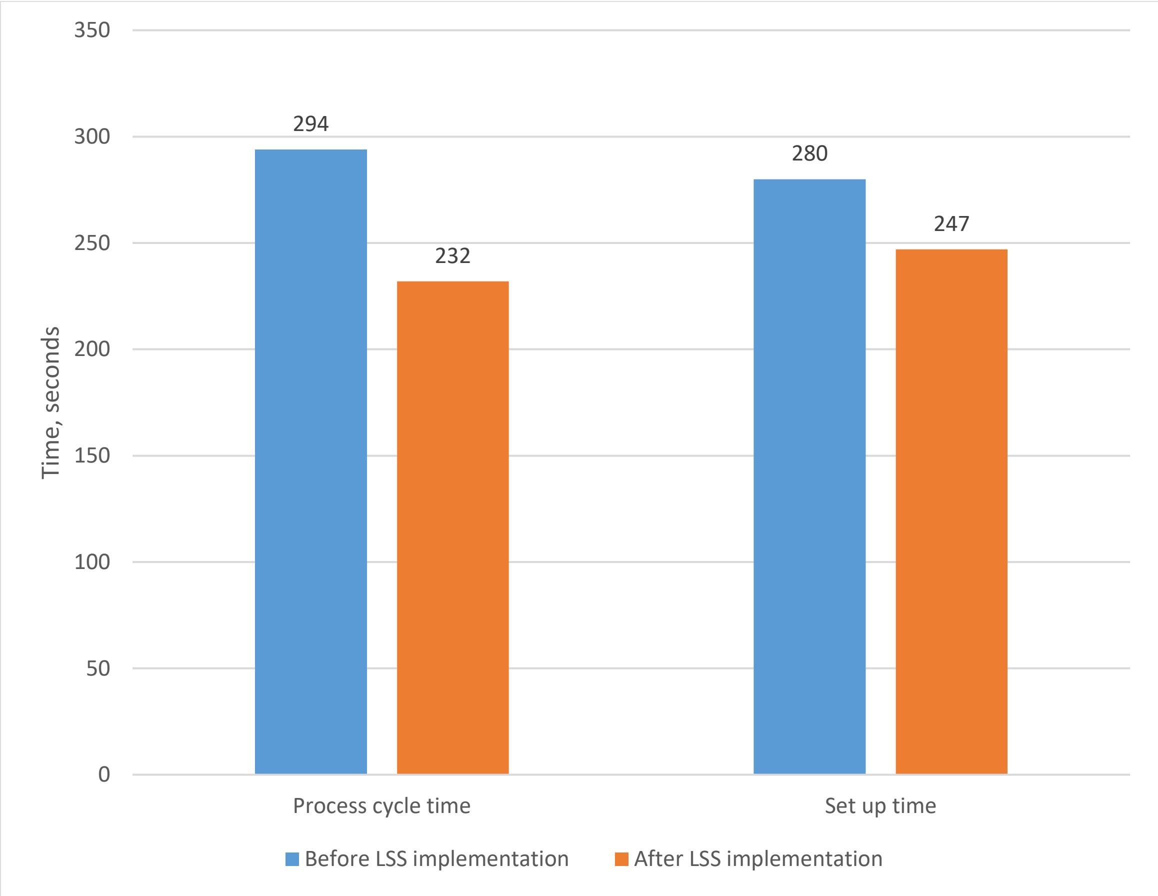

Fig. 29. Time Savings from LSS Application

Process cycle efficiency of the automated soldering process before the LSS application was calculated to be at 27.35% by total process time out of the value-added activities. In addition, Lean processes are indicated to be those that have a process cycle efficiency percentage higher than 25%. Moreover, as of current results indicate, the process could be evaluated as a Lean process, but after the elimination of non-value-added activities in the process, the PCE has been calculated to be at 32.78%. Furthermore, the process cycle efficiency increased by 5.43% as shown in Fig. 30, indicating that after the improvements, the process is more optimized, reducing fatigue from the operators as less walking time is needed for the process.

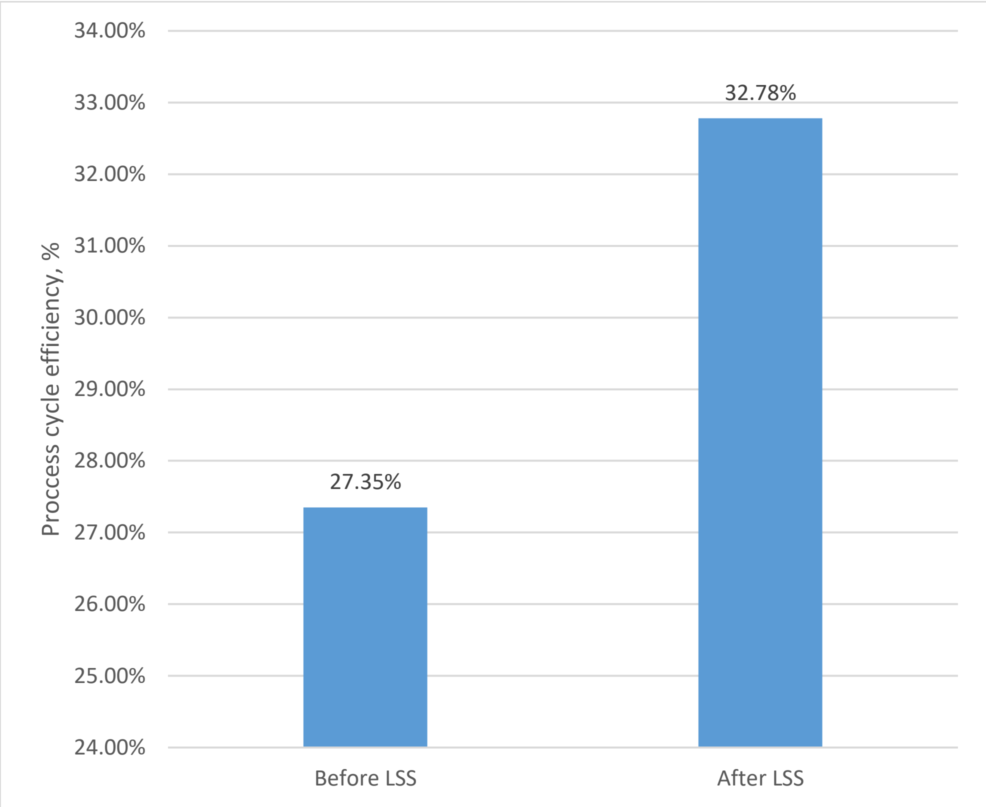

Fig. 30. Process Cycle Efficiency Improvement from LSS Application

As process cycle efficiency has been increased and process cycle time has been reduced economic benefit could be evaluated. In addition, from a single cycle in the automated battery soldering station, 12 finished products are made, meaning that before LSS implementation, the cycle time of a single product through this process was calculated to be at 24.5 seconds, while after improvements, it was calculated to be at 19.3 seconds. The calculations for the daily production of units were done by taking into consideration the setup time and the total time given during the shift. Moreover, currently there are three shifts implemented for the battery soldering process, which contain 7 hours of work time and 1 hour of lunch time for the operators. Therefore, it was calculated that one shift before LSS application could produce up to 1017 finished products by subtracting the setup time of 280 seconds from the whole shift time of 25200 seconds and dividing it by the cycle time for one PCB, which is 24.5 seconds. Moreover, after the LSS application, the output would be increased to 1292 finished products by subtracting 247 seconds out of 25200 and dividing the number by the single process time, which is 19.3 seconds. As a result, the output for single shifts has increased by 275 units, as seen in Fig. 31.

The average wage in the company has been evaluated to be 2600 EU. As there are three shifts in this process, the daily output of finished products before the LSS application reached 3051 units, after the improvements daily output would be estimated to be 3876 units, leading to 825 more units being produced daily. Calculation of financial benefit could be made through the percentage of the finished products increased daily, meaning with the same amount of money for the wages, a higher result would be yielded. Moreover, after LSS applications, the daily output increased by 21.28%. Furthermore, to reach the same amount of units produced before DMAIC application as after the improvements in the automated soldering process, it would cost 553.28 EU extra in operator wages, which was evaluated from the output increase and the current average wage in the company. Therefore, after Lean Six Sigma application, the company saves monthly 1659.84 EU, as with the same number of wages, we reach 21.28% higher output.

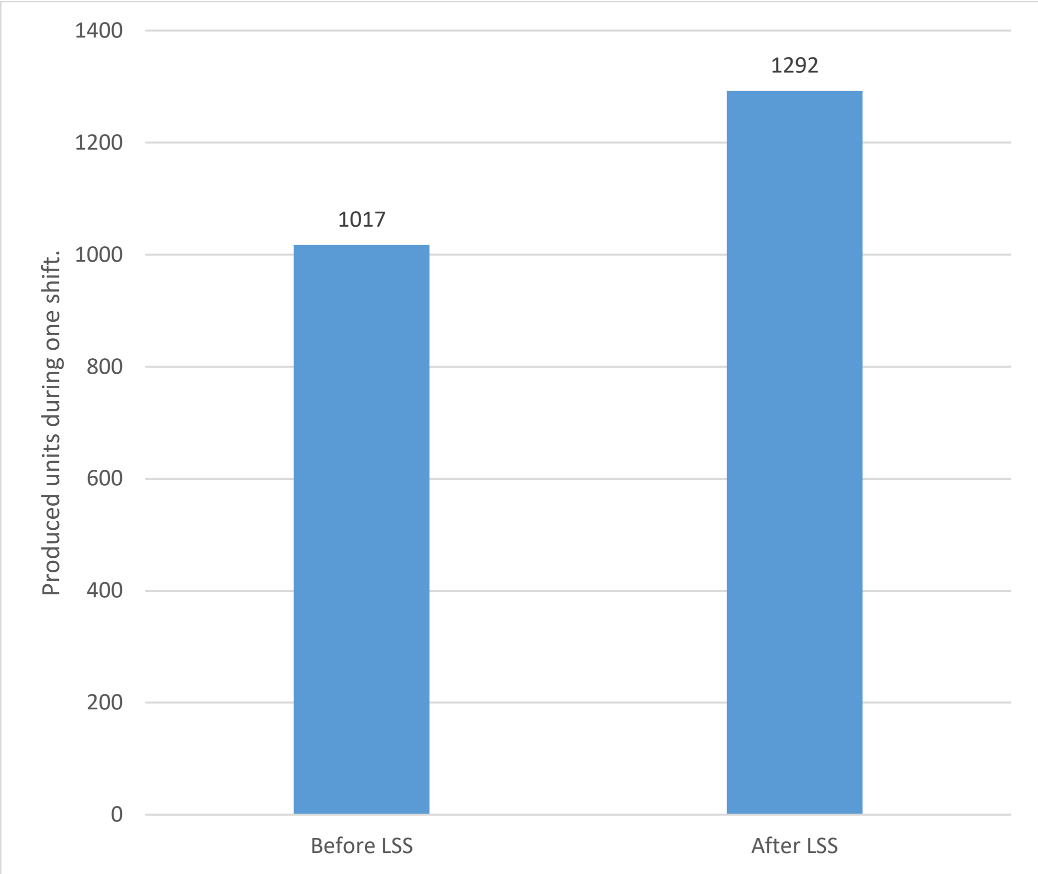

Fig. 31. Results of Unit Production Increase After LSS Project.

DMAIC application in a production process is not limited only to economic benefits to the manufacturer. Moreover, after the suggested improvements are implemented in the automated battery soldering process, the social aspect of the manufacturing process also benefits. Furthermore, by utilizing the Control phase of the LSS application, the process is standardized by implementing a Standard Operating Procedure (SOP), which ensures that the process steps are defined, and no interpretation can be made during the automated battery soldering process. Therefore, eliminating any uncertainty and doubt from the employees, which elevates the mood and effectiveness of the employees. Moreover, the introduction of a buddy system program in the soldering process ensures that all employees are kept up to date with the newest improvement implementations, and the knowledge of the current process is kept up to date by ensuring that colleagues evaluate each other's work, bringing a more collaborative approach to the workplace. In addition to the improvements in collaboration and erasing of doubt, another suggestion should be implemented, which is Lean thinking related to continuous improvement. Moreover, continuous improvement empowers the employees to participate in the process of improvement planning and implementation. As a result of empowering employees to suggest improvement areas or find key root causes of certain issues, it makes employees feel heard by the upper management, which also improves the mood and productivity in the workplace. In conclusion, by applying DMAIC with lean tools, the improvements can be seen not only financially but also socially in production as employees feel more empowered as their doubts and uncertainties are erased, in addition to increasing collaboration between the employees.

4.1. Chapter Summary

The calculation of LSS implementation in the automated soldering process was done to estimate the current process cycle efficiency and daily outputs, and the same measures after the suggested improvements. Moreover, the evaluation of financial benefits was done, where the evaluation of 1659.84 EU monthly savings was deducted. In addition to the benefits from an economic perspective, it is also considerable to mention that LSS application has been proven to have social benefits, bringing collaboration between operators, positively affecting the mood of the employees, and reducing uncertainty and doubt while doing the process activities. Furthermore, the calculations proved that process efficiency improvements and standardization are essential for economic advantages for the company compared to the competitors, therefore, LSS is a great tool for social and economic development in the company.

Conclusions

1. After Lean Six Sigma methodology analysis, it was found that the DMAIC cycle can be applied to manufacturing companies to improve process cycle efficiency or reduce defect rates. It was found that companies are still struggling to achieve the 6^{th} sigma operating level.

2. After analyzing Lean Six Sigma applications in various production processes, it was found that on average, the implementation improved process cycle efficiency by 8.54%. No proper methodology implementation was found for electronic product manufacturing processes.

3. Lean Six Sigma was implemented in an electronic component production process, leading to improvement suggestions. The battery soldering operation was analyzed, where process cycle efficiency was evaluated to be at 27.35%. The main root causes were found to be defective units in the battery soldering operation.

4. Comparison of achieved efficiency results before and after LSS implementation was made. It was calculated that process cycle efficiency would increase by 5.43% if suggested improvements were implemented. The cycle time of the automated battery soldering process was reduced by 35 seconds.

5. The economic benefits for the electronic product manufacturer were calculated to be 1659.84 EU a month as the output of the battery soldering station increased by 21.28%. It was found that Lean Six Sigma implementation in the electronic product manufacturer's production processes could be applied for financial and social benefit.

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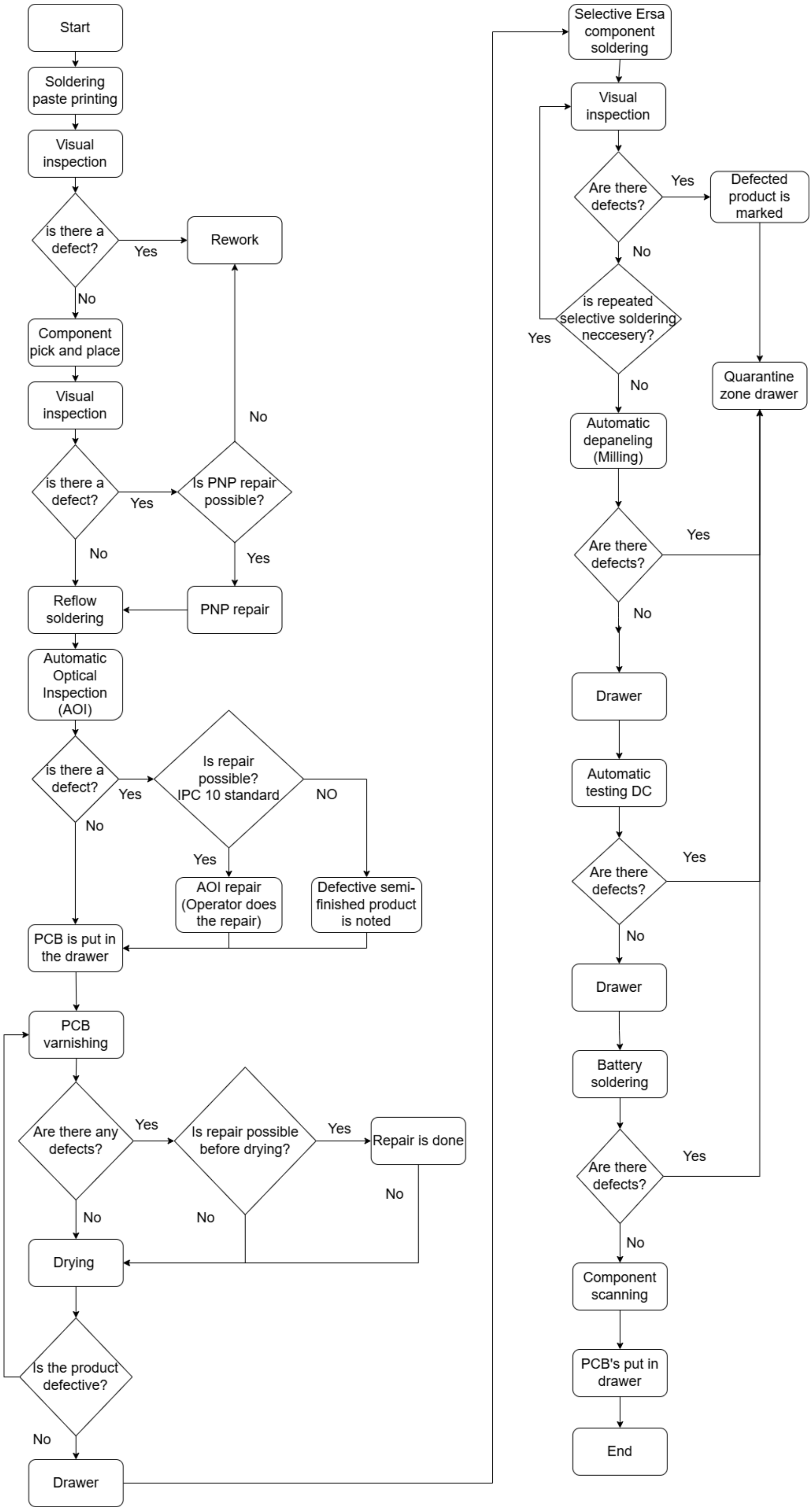
Appendices

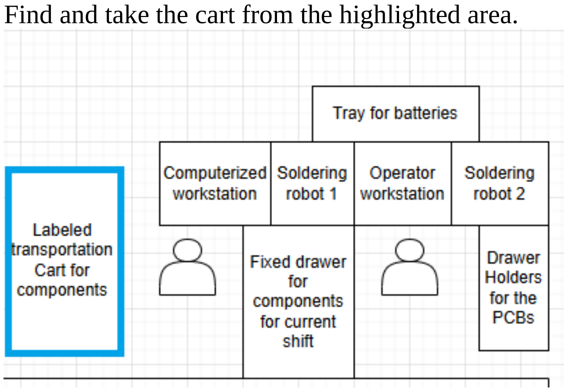
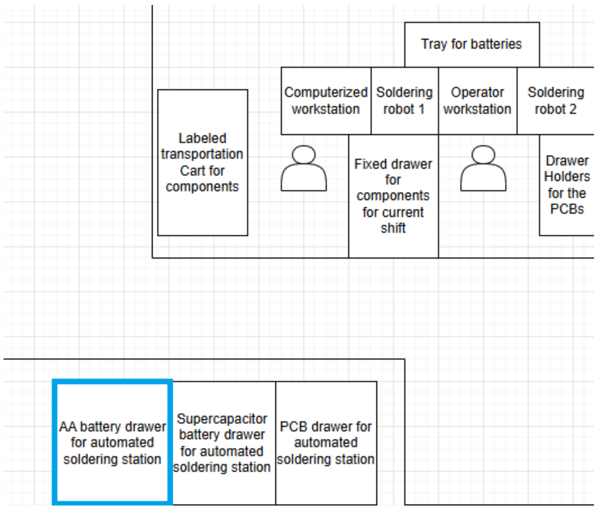
Appendix 1. Electronic Line Process

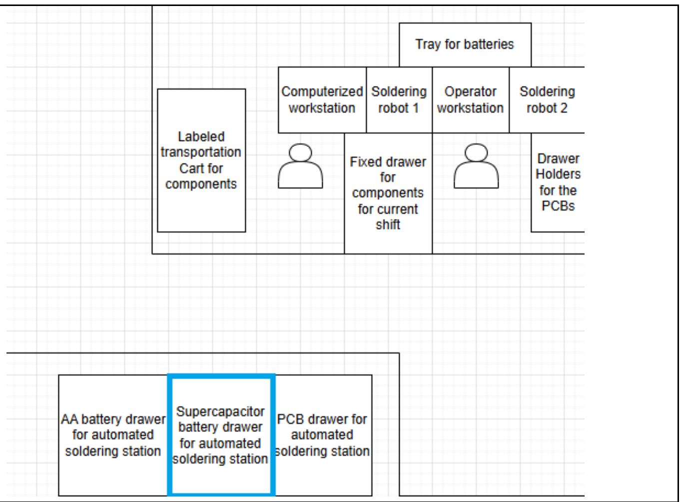
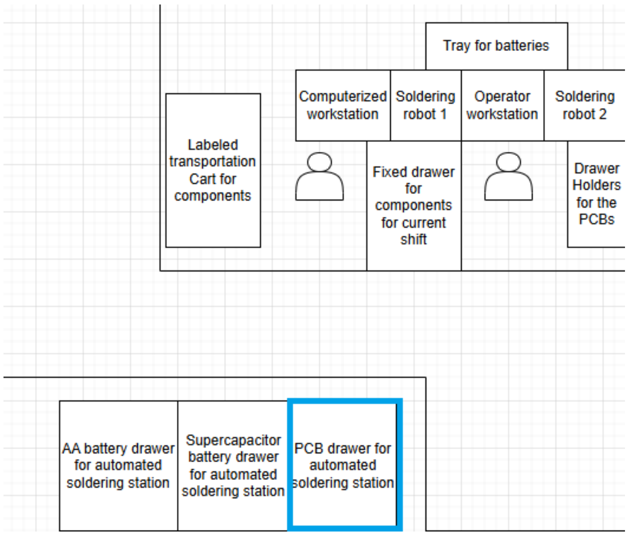
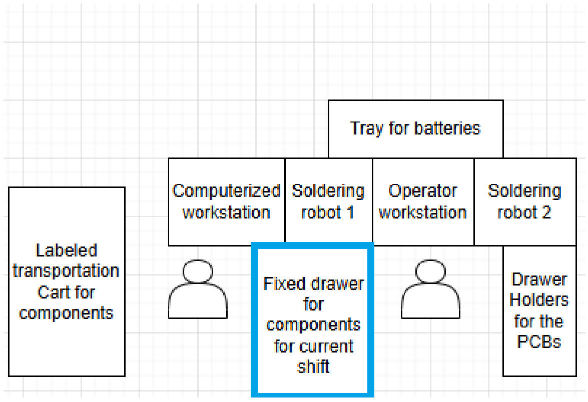


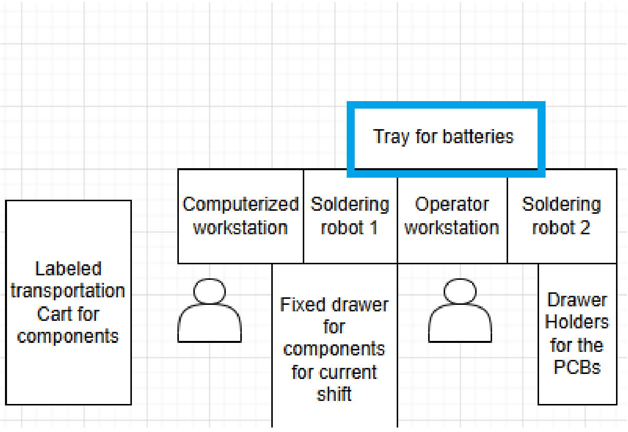
Appendix 2. Standard Operating Procedure for Automated Battery Soldering Process

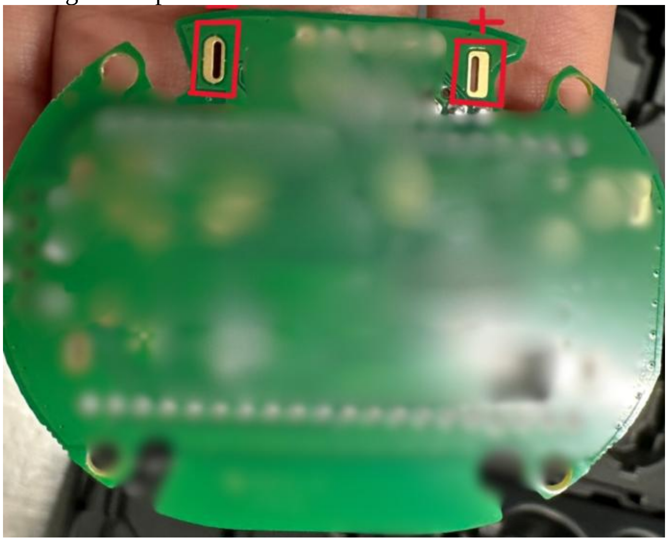
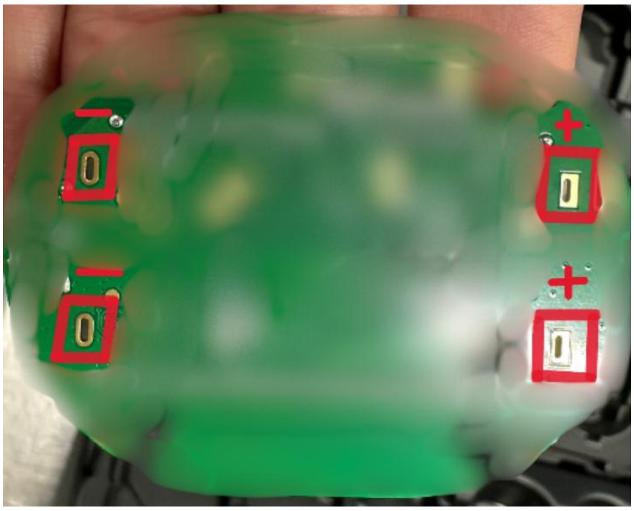
STANDARD OPERATING PROCEDURE Standardized Work instruction	Status: **Final Version** Revision: 1 Rev. Date: 25/04/2025
Procedure Number ASO0001	

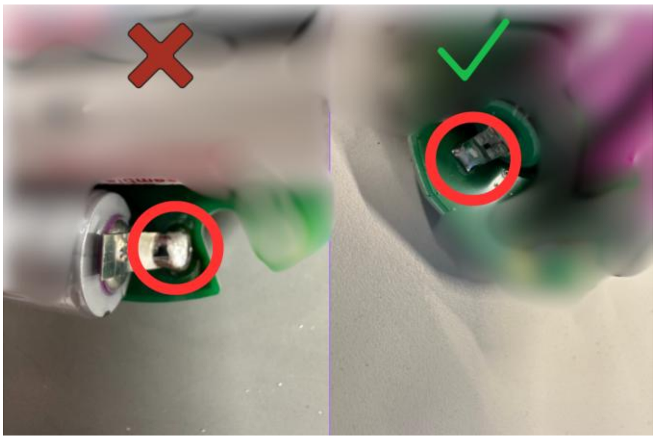
Setup process steps

Task	Description	Sub-Task	Instructions
1.	Take the labeled cart	1.1	Find and take the cart from the highlighted area. 
2.	Pick up prepared AA batteries	2.1	Pick up AA battery trays and put them in the bottom of the tiered cart. 
		2.2	Put the trays on top of each other in three rows for a total amount of 50 trays.
3.	Pickup supercapacitors	3.1.	Pick up Supercapacitor battery trays and put them in the middle of the tiered cart.

			
		3.2	Put the trays on top of each other in two rows for a total amount of 20 trays
4.	Pick up PCBs from the drawer prepared for automated soldering station	4.1	Pick up PCBs and put them in the top part of the tiered cart 
		4.2	Put the trays on top of each other stacked up to 10 trays in one row. (needed amount 95 trays or 9.5 rows)
5.	Place the gathered materials in the drawer	5.1	Put all AA battery trays in the lowest shelf of the drawer. Supercapacitors at the middle shelf and PCBs at the top shelf. 
6.	Turn on the computer and launch HORA program	6.1	Press the power on button on the computer, login using the given credentials

		6.2	Launch two HORA applications for both soldering robots and login to the account through given credentials
			On both application windows select each of the automated soldering stations
7.		7.1	Start up both automated soldering robots by turning the key to the "Run" position and pressing the start/stop button 
8.		8.1	Place 6 trays of batteries and supercapacitors in front of the operating station. 
Automated soldering station process steps			
9.	Put circuits boards in the holder	9.1	Put 12 circuit boards from the drawer to the PCB holder in front
		9.2	Put the PCBs in order from left to right (12 PCBs)
10.	Put the supercapacitors in the PCBs	10.1	Put 12 supercapacitors from the drawer into the PCBs on upper connection

		10.2	Put supercapacitor battery points correctly, left side minus and right side plus. 
11.	Put AA batteries in the circuit board	11.1	Put two AA batteries in each of the PCBs from left to right.
		11.2	The battery connection should be placed in the same order as the supercapacitors, on the left the negative connection and on the right the positive connection 
12.	Put upper holder	12.1	Pu upper holder to lower holder by aligning it with the batteries
		12.2	Clamp upper holder to the lower part of the holder
13.	Take out the finished product in the soldering station	13.1	Take out finished products with the holder and put in the newly prepared holder in the automated soldering station
		13.2	Remove the upper holder from the finished products.
14.	Visual defect inspection	14.1	Inspect every PCB if the batteries were properly soldered, the solder joint should not have excess on the upper part of

			the PCB. 
15.	Manually resoldering defective PCBs	15.1	Manually resolder the defected PCBs as the solder material goes through the other side.
16.	Putting finished products in the tray	16.1	Put finished products in the tray.