Final Report - Assembly Project

Handheld Vacuum Cleaner

In the Course:

MG2040 VT25 Assembly Technology

Presented by:

Project Group C

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1 Introduction

This report documents the analysis and optimization of the assembly process for a commercially available handheld vacuum cleaner. The project was carried out as part of the course ***MG2040 Assembly Technology*** at KTH Royal Institute of Technology during the spring term of 2025. The aim of the project was to apply theoretical knowledge from the course in a practical context by analyzing a real product and designing an efficient and ergonomic assembly process based on engineering principles.

Working as a team of five students, we systematically investigated the structure, function, and assembly logic of the product. The process began with disassembly and documentation of all parts, followed by the creation of a detailed CAD model using Solid Edge. This model served as the basis for a 3D exploded view, a structured Bill of Materials (BOM), and further functional analysis.

Subsequently, the team defined a preliminary assembly sequence, developed a precedence diagram, and analyzed alternative assembly paths using a Liaison Sequence Diagram (LSD). A time study was conducted with four manual test runs to obtain realistic assembly data, which enabled line balancing based on different optimization methods. In addition, workstation layouts, fixtures, and ergonomic principles such as reach zones and visual management were integrated into a first concept for a manual assembly line.

A detailed Design for Assembly (DFA) analysis was carried out for both manual and automated assembly scenarios. The evaluation included part-level and product-level criteria and led to concrete improvement suggestions such as component modularization, unified screw selection, and improved cable routing. The project concludes with an economic evaluation comparing manual and automated assembly scenarios, highlighting the trade-offs in terms of investment, scalability, and return on investment.

This report is structured according to the main phases of the project and provides a comprehensive insight into how theoretical assembly concepts can be translated into practical, data-driven engineering decisions.

2 Product Description and Representation

2.1 Basic Product Information

The product analyzed in this project is a compact handheld vacuum cleaner designed for removing both dry and wet dirt (see Figure 1). It is lightweight, battery-powered, and ergonomically shaped for one-handed use, making it ideal for cleaning small or confined spaces.
The vacuum comes with two interchangeable attachments: a brush for dust and delicate surfaces, and a rubber nozzle for collecting liquids. It features a container with a total capacity of 400 ml, including up to 100 ml for wet dirt. A full battery charge takes approximately four hours and provides up to 20 minutes of operation [1].

The device includes an On/Off switch on the handle and a push button further along the housing that allows for easy removal of the filter unit, which can be twisted and pulled out for emptying. The main functional units include the motor module (delivered as a preassembled part), the plastic housing, filter system, and user interface components. Assembly is achieved through a combination of snap-fit connections and screws.

Although the product is delivered with a wall-mounted holder, this project focuses solely on the vacuum cleaner itself, excluding accessories.

Figure 1. Product image from Clas Ohlson [1]

2.2 CAD Model

To support a detailed analysis of the product and to gain a deeper understanding of its components and subassemblies, a comprehensive CAD model of the handheld vacuum cleaner was created using Solid Edge. Based on this model, a 3D exploded view was generated to visualize the internal structure and spatial relationships between the parts. This step is essential for identifying the function of individual components and understanding the overall assembly process, serving as a foundation for further analysis in areas such as process planning, design for assembly, and line balancing.

2.2.1 Parts and Exploded View

To provide a comprehensive understanding of the product's structure and assembly, a 3D exploded view of the vacuum cleaner was created (see Figure 2). This visual representation allows readers to grasp the assembly logic and spatial relationships between components, even without access to the physical product. It plays a crucial role in identifying the correct assembly sequence and supports all further steps in process planning and analysis.

The exploded view offers a high-level overview of the product's major subassemblies and connection points. Following this, a detailed CAD-based parts list is presented (see Table 1), which documents all individual components modeled in Solid Edge. This structured overview serves as a foundation for the subsequent functional decomposition, assembly sequence definition, and Design for Assembly (DFA) evaluation.

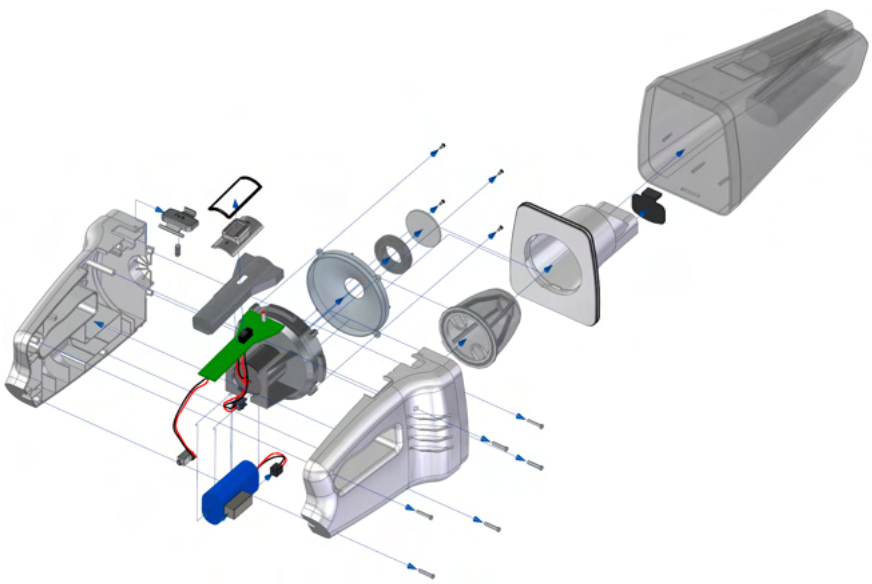
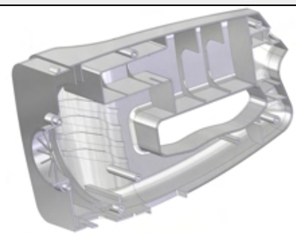
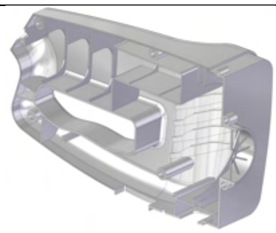
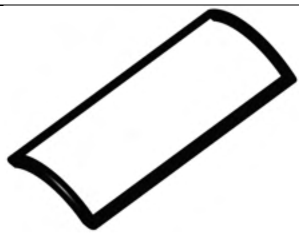
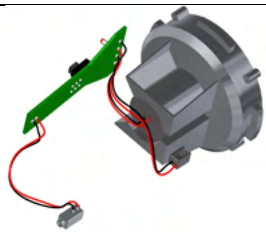
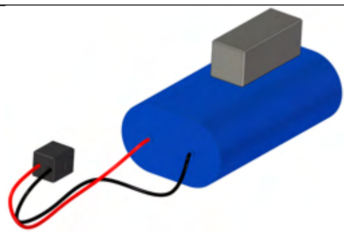
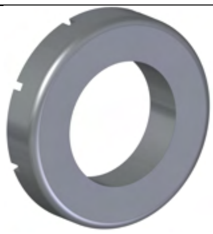
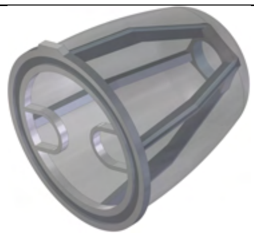
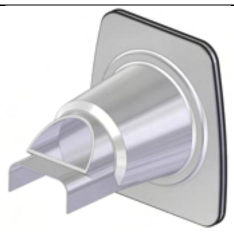


Figure 2. Exploded View in CAD

Table 1. Overview - Created parts in CAD

Name	Picture
Housing left side	
Housing right side	
On/Off button	
Rubber ring On/Off button	
Foam rubber	
Release button	

Long screw	
Spring	
Motor/Turbine/Circuit	
Battery	
Turbine cover	
Sealing ring	

Circuit case	
Short screw	
Shell	
Rubber flap	
Vacuum filter	
Filter holder	

2.2.2 Subassemblies

To simplify the analysis and improve the clarity of the product structure, the handheld vacuum cleaner was divided into three main subassemblies (see Table 2). Each subassembly groups functionally and physically related components and represents a logical unit within the overall assembly process.

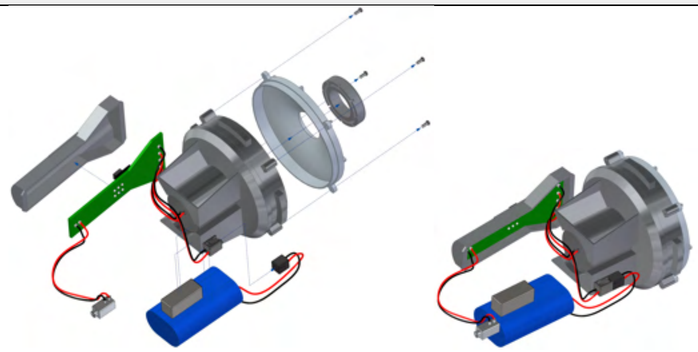
The first subassembly consists of the motor, battery, and control printed circuit board (PCB). This unit serves as the functional core of the product. It combines energy supply, control logic, and mechanical suction power in a compact configuration, minimizing assembly effort during final integration.

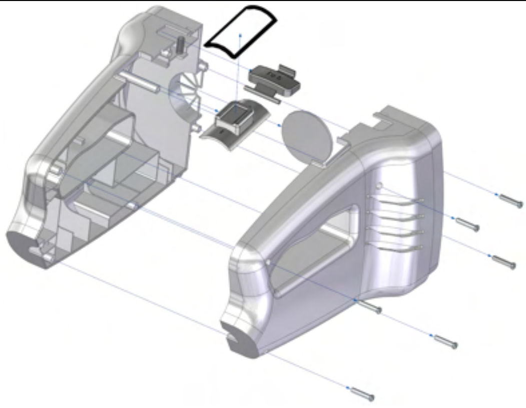
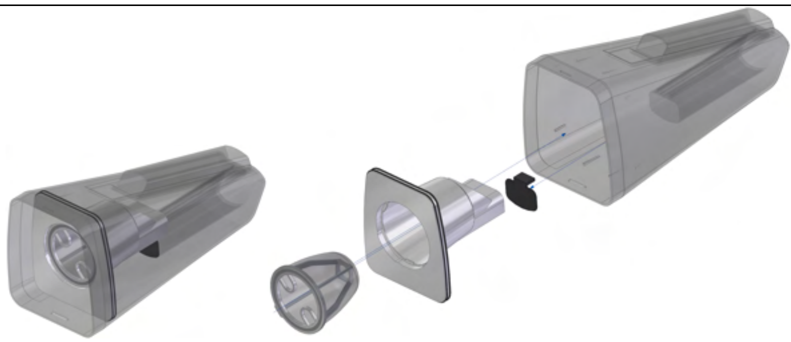
The second subassembly is the housing, which is composed of two symmetrical plastic shells that enclose the internal components. It also integrates several user interface elements such as the On/Off switch and the filter release button. The housing ensures mechanical protection, structural stability, and ergonomic handling of the device.

The third subassembly, referred to as the shell, includes the external dust container, filter unit, and sealing elements. This part of the product is responsible for collecting dry and wet dirt and allows the user to easily remove, empty, and reassemble the container. Its modular design enables user interaction while maintaining separation from internal electronics and drive components.

Together, these three subassemblies form the complete product architecture and serve as the basis for the development of the assembly sequence and line balancing strategy.

Table 2. Subassemblies in CAD

Name	Picture
Motor/Battery/PCB	

Housing	
Shell	

2.3 BOM including Part Codes and Numbering

To systematically categorize all components of the vacuum cleaner, a Bill of Materials (BOM) was created based on the exploded CAD view of the product (see Figure 3 and Table 3). Each part was assigned a clear and descriptive Part ID, using prefixes that correspond to its respective subassembly. This structured identification system ensures consistent traceability and facilitates the analysis of the product architecture.
The BOM includes detailed information for each part, including subassembly assignment, part name, material, and required quantity. By deriving the BOM directly from the exploded view, both the spatial relationships and the functional grouping of parts are accurately reflected. This detailed component breakdown forms the basis for further steps in assembly planning, process evaluation, and Design for Assembly (DFA) assessment.

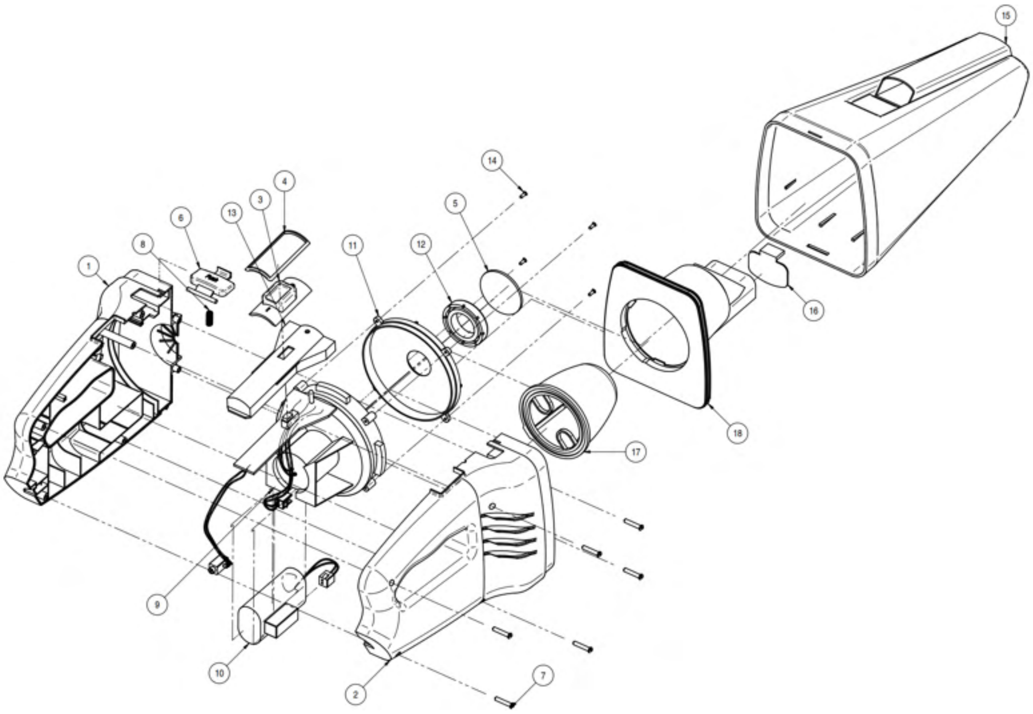


Figure 3. Exploded View with BOM nodes

Table 3. BOM Handheld Vacuum Cleaner

No.	Part ID	Sub Assembly	Part Name	Quantity	Material
1	HOU-1001	Housing	Housing left side	1	Plastic (black)
2	HOU-1002	Housing	Housing right side	1	Plastic (black)
3	HOU-1003	Housing	On/Off button	1	Plastic (silver)
4	HOU-1004	Housing	Rubber Ring on/off button	1	Rubber (black)
5	HOU-1005	Housing	Foam rubber	1	Rubber (black)
6	HOU-1006	Housing	Release button	1	Plastic (silver)
7	HOU-1007	Housing	Long Screws	6	Steel (silver)
8	HOU-1008	Housing	Spring	1	Steel (silver)
9	MOT-2001	Motor/Battery	Motor / Turbine / Platine	1	Metal, plastic
10	MOT-2002	Motor/Battery	Battery	1	Lithium, plastic, metal
11	MOT-2003	Motor/Battery	Turbine cover	1	Plastic (black)
12	MOT-2004	Motor/Battery	Sealing ring	1	Rubber (black)
13	MOT-2005	Motor/Battery	Circuit case	1	Plastic (black)
14	MOT-2006	Motor/Battery	Short Screws	4	Steel (silver)
15	SHE-3001	Shell	Shell	1	Plastic (clear grey)
16	SHE-3002	Shell	Rubber flap	1	Rubber (black)
17	SHE-3003	Shell	Vacuum filter	1	Plastic/nylon (black/grey)
18	SHE-3004	Shell	Filter holder	1	Plastic (black)

3 Product Function Analysis and Mapping

3.1 Part and Function Overview

Table 4 provides a structured overview of all individual components used in the handheld vacuum cleaner. Each row in the table represents a specific part, identified by a unique Part No. and grouped according to its associated subassembly. The description column outlines the part's name and function, while the material column specifies the material composition of each component. The dimensions column provides size information relevant to space allocation and handling considerations.

Furthermore, the assembly angles (α and β) are listed for each part, as they are essential for analyzing handling times during manual assembly. A visual reference is also included through a picture column, supporting part identification and documentation clarity.

It should be noted that the motor unit, comprising the motor, turbine housing, and circuit board, will be treated as a single component throughout the remainder of the project. This is due to the fact that the motor shaft is press-fitted into the turbine, making disassembly and reassembly impractical without damaging the parts. As a result, it is assumed that this subassembly is delivered as a preassembled unit by the supplier.

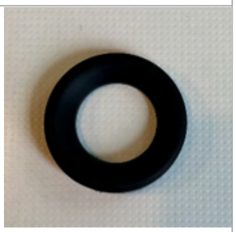
Table 4. Parts and Functions Overview

Part ID	Sub assembly group	Description	Dimensions (l x w x h)	Angles	Function	Picture
SHE-3003	Shell	Vacuum filter	Diameter = 67 mm Length = 65 mm	α = 360° β = 30°	Collects dust and dirt that enters the vacuum.	 

SHE-3004	Shell	Filter holder	Length = 107 mm Width = 101 mm Height = 111 mm	α = 360° β = 360°	Holds the filter in place. It is used to fix the filter, so it does not move.	
SHE-3002	Shell	Rubber flap	Length = 38 mm Width = 27 mm Height = 11 mm	α = 360° β = 360°	Acts as a one-way valve that allows debris to enter the dust container but prevents it from escaping, helping to store debris securely and maintain suction efficiency	
SHE-3001	Shell	Shell	Length = 257 mm Width = 109 mm Height = 123 mm	α = 360° β = 360°	The outside shell is used for creating a vacuum to suck up dirt in the nozzle.	

HOU-1007	Housing	Long Screws	Diameter= 4,5 mm Length = 18 mm	α = 360° β = 0°	Holds the housing-sof the vacuum cleaner to-gether.	
HOU-1008	Housing	Spring	Diamter = 4 mm Length = 12 mm	α = 180° β = 0°	Used for the start button, to turn on and off the vacuum.	
HOU-1005	Housing	Foam Rubber	Diameter = 40 mm Height = 2 mm	α = 180° β = 0°	Extra filter to ensure that no dust gets into the electrics.	
HOU-1003	Housing	On/Off but-ton	Length = 50 mm Width = 26 mm Height = 12 mm	α = 360° β = 360°	Turn the vacuum on or off.	
HOU-1004	Housing	Rubber Ring on/off button	Length = 52 mm Width = 28 mm Height = 12 mm	α = 180° β = 180°	Attached to the on/off but-ton, for it to function in the on and off positions.	

HOU-1006	Housing	Release button	Length = 30 mm Width = 34 mm Height = 9 mm	α = 360° β = 360°	Separate the base of the vacuum and the shell.	
HOU-1001	Housing	Housing left side	Length = 213 mm Width = 123 mm Height = 58 mm	α = 360° β = 360°	The left side of the holder. Is used to hold the vacuum, attachments such as the on/off button, push button and the shell is placed on this part. It also holds the electronics.	 
HOU-1002	Housing	Housing right side	Length = 213 mm Width = 123 mm Height = 58 mm	α = 360° β = 360°	The right side of the holder. Is used to hold the vacuum, attachments such as the on/off button,	 

					push button and the shell is placed on this part. It also holds the electronics.	
MOT-2003	Motor/Battery	Turbine cover	Diameter = 90 mm Height = 22 mm	α = 360° β = 90°	Covers the turbine and contributes to the vacuum effect.	
MOT-2004	Motor/Battery	Sealing ring	Diameter = 39 mm Height = 8 mm	α = 360° β = 90°	Put on the turbine covers end and is used to create a vacuum seal.	
MOT-2005	Motor/Battery	Circuit case	Length = 102 mm Width = 45 mm Height = 15 mm	α = 360° β = 360°	A case to protect the circuit.	

MOT-2001	Motor/Battery	Motor / Turbine	Diameter = 101 mm Height = 75 mm	α = 360° β = 360°	The motor blades turn fast and create suction that then creates the vacuum.	
MOT-2002	Motor/Battery	Battery	Length = 62 mm Width = 22 mm Height = 63 mm	α = 360° β = 360°	The battery powers the motor.	

3.2 Product Mapping (Liaison Diagram)

Figure 4 shows the Liaison Diagram, which illustrates the structural and assembly relationships between the three main subassemblies of the handheld vacuum cleaner, Motor/Battery/PCB, Housing, and Shell and their respective components. These subassemblies are highlighted in blue and represent the core functional units of the product. Each subassembly is composed of multiple parts, shown in grey, which are connected either within the same group or across different subassemblies.

The arrows in the diagram indicate how the individual components are assembled relative to one another, while the numbers along the arrows refer to the type of connection used. According to the legend in the bottom left corner, three connection types are distinguished: (1) screwed connection, (2) insertion (e.g., press-fit or guided placement), and (3) click connection (snap-fit). This classification is important for later analysis steps, particularly when evaluating assembly time, tool usage, and potential automation.

The Liaison Diagram complements the Bill of Materials introduced in Chapter 2.3 by providing a visual representation of the product's structural hierarchy and the interaction between mechanical interfaces. It also serves as a useful reference for defining assembly sequences and for assessing the overall design from a Design for Assembly (DFA) perspective.

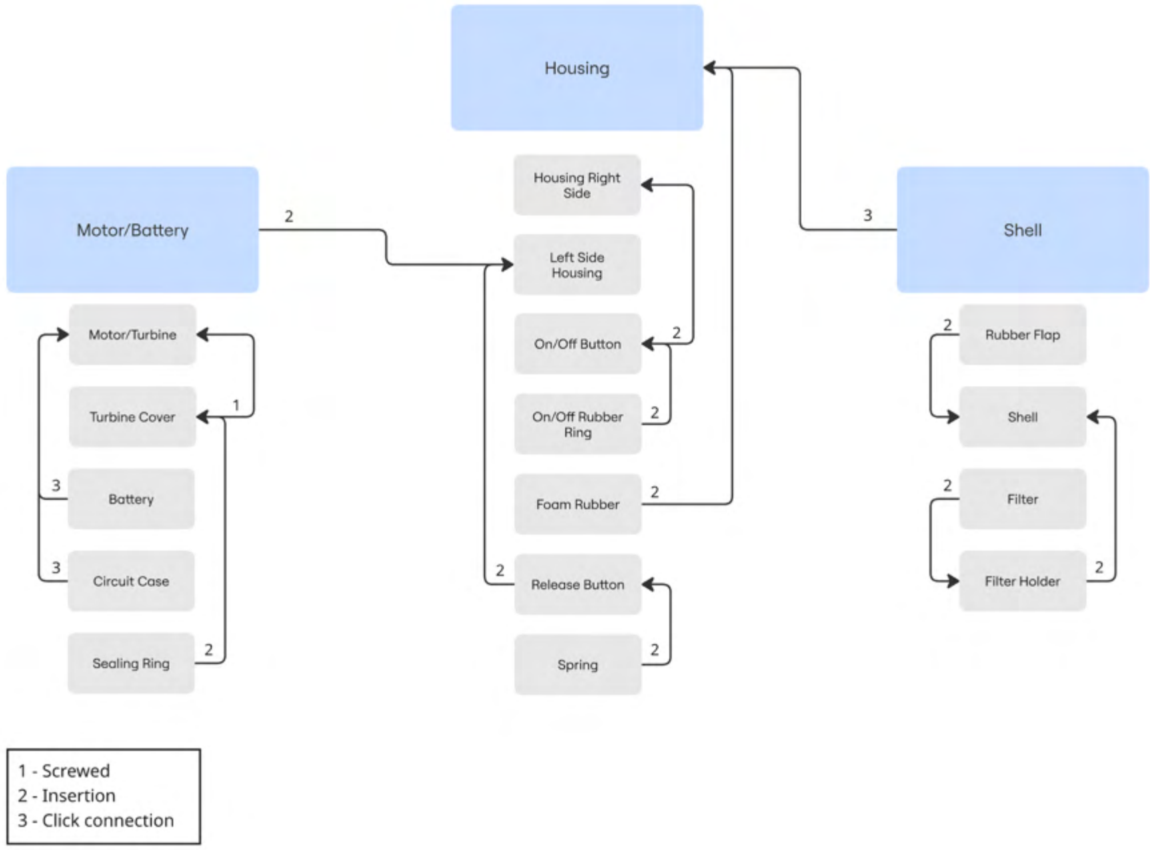


Figure 4. Liaison Diagram of the Vacuum Cleaner

4 Assembly Process Definition and Sequence

4.1 Assembly Operations Overview

The following section outlines a preliminary sequence of the manual assembly process for the handheld vacuum cleaner. At this stage, no precedence analysis or line balancing has been performed; the operations are documented based on observed dependencies, logical assembly flow, and physical constraints. This initial breakdown serves as a foundation for further work on process optimization, balancing, and workstation planning. Each step is described in continuous prose, capturing essential technical and ergonomic considerations.

Operation 1 – Connecting Motor Unit to Battery

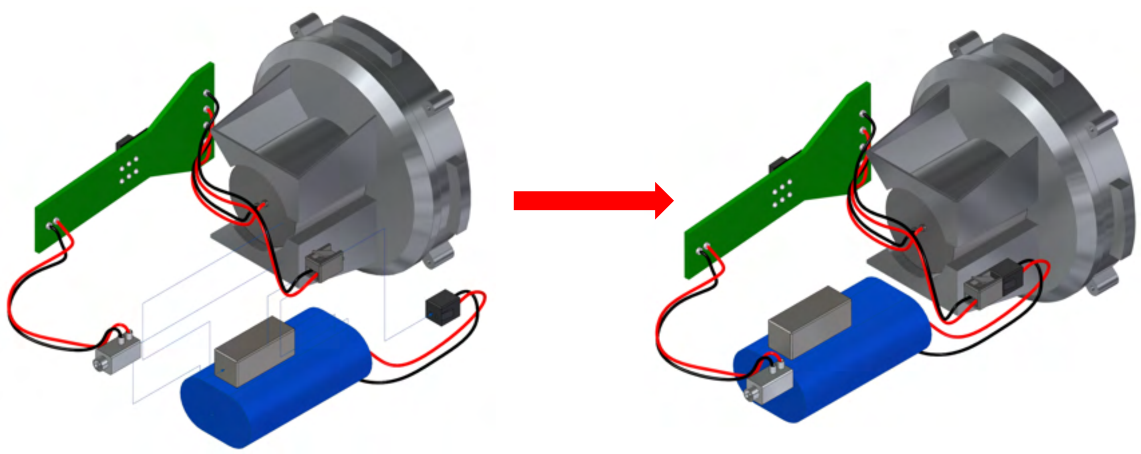


Figure 5. CAD image - Operation 1

The motor assembly, consisting of the turbine, electric motor, control board, and charging port, is delivered as a preassembled purchased component. In the first step of the process, this motor unit is connected to the battery (see Figure 5). The electrical connection is established using a plug-in connector, allowing a quick and secure interface between the motor unit and the power supply.

Operation 2 – Insertin Control PCB into the Cover

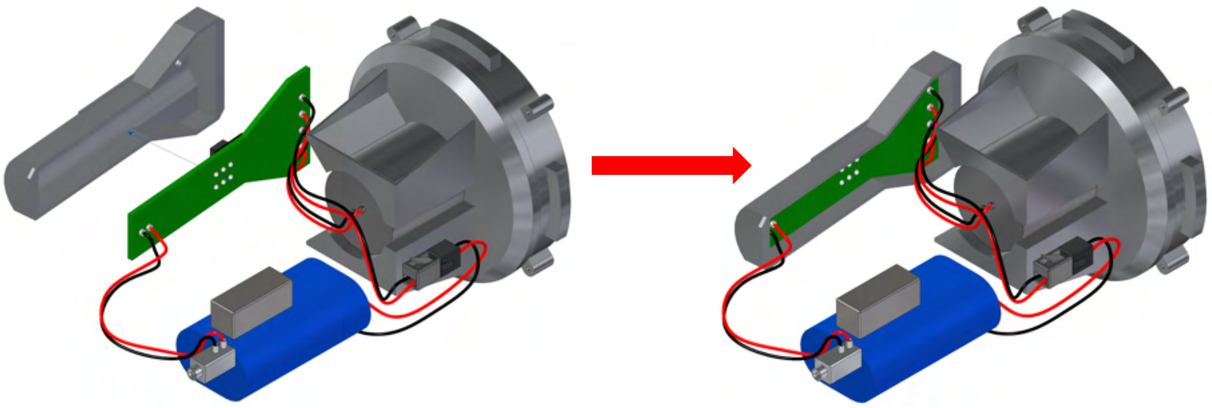


Figure 6. CAD image - Operation 2

The control PCB is inserted into its designated position within the housing. It is secured by a snap-fit mechanism, eliminating the need for additional fasteners and ensuring proper alignment through integrated molded guides (see Figure 6). However, this connection requires correct placement on the first attempt, as the snap-fit design does not allow disassembly without causing damage to the components or the housing structure.

Operation 3 – Mounting the Turbine Cover

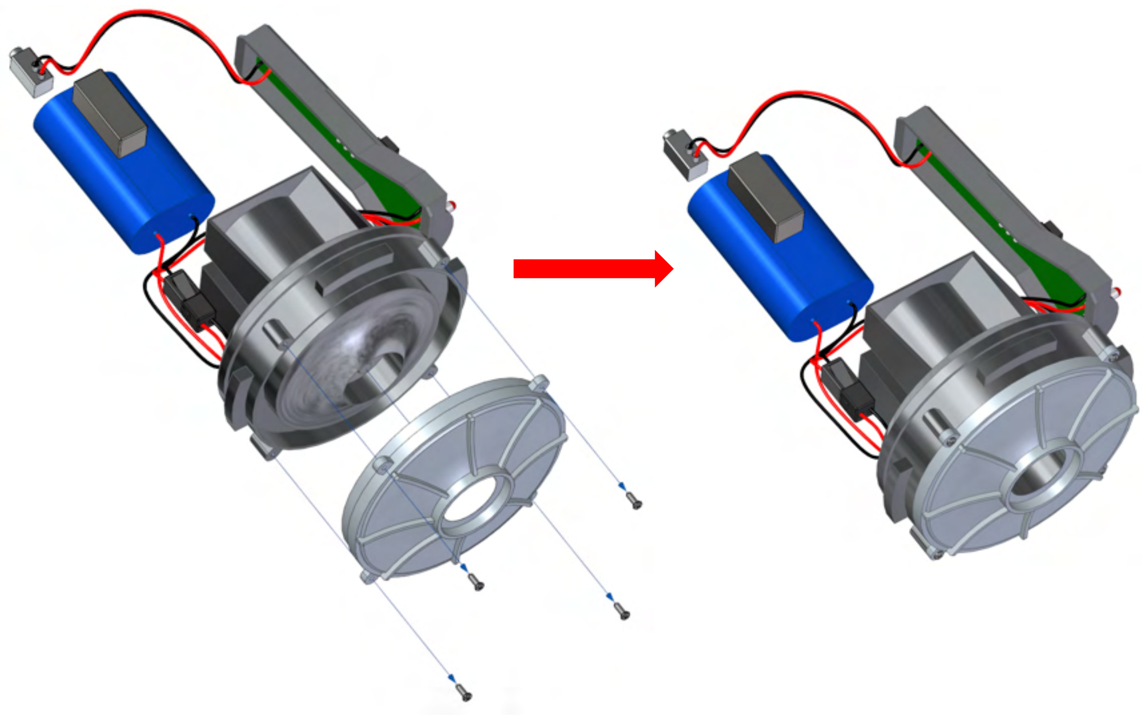


Figure 7. CAD image - Operation 3

A plastic cover is positioned on top of the turbine and fixed using four screws (see Figure 7). This enclosure protects the turbine components and finalizes the mechanical integration of the motor module.

Operation 4 – Installing Rubber Ring

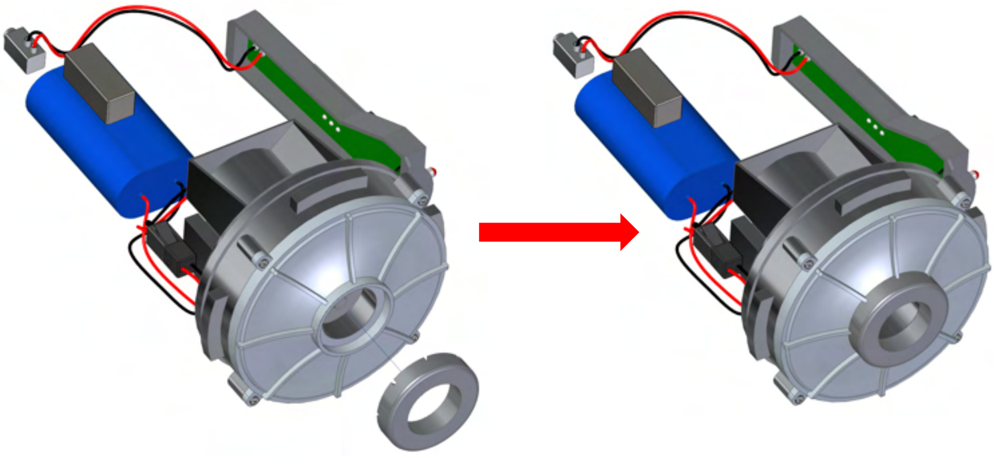


Figure 8. CAD image - Operation 4

A rubber buffer ring is mounted onto the turbine cover, by placing the respective slots of the rubber ring on the ribs of the cover (see Figure 8).

Operation 5 – Placing Subassembly into the Left Housing

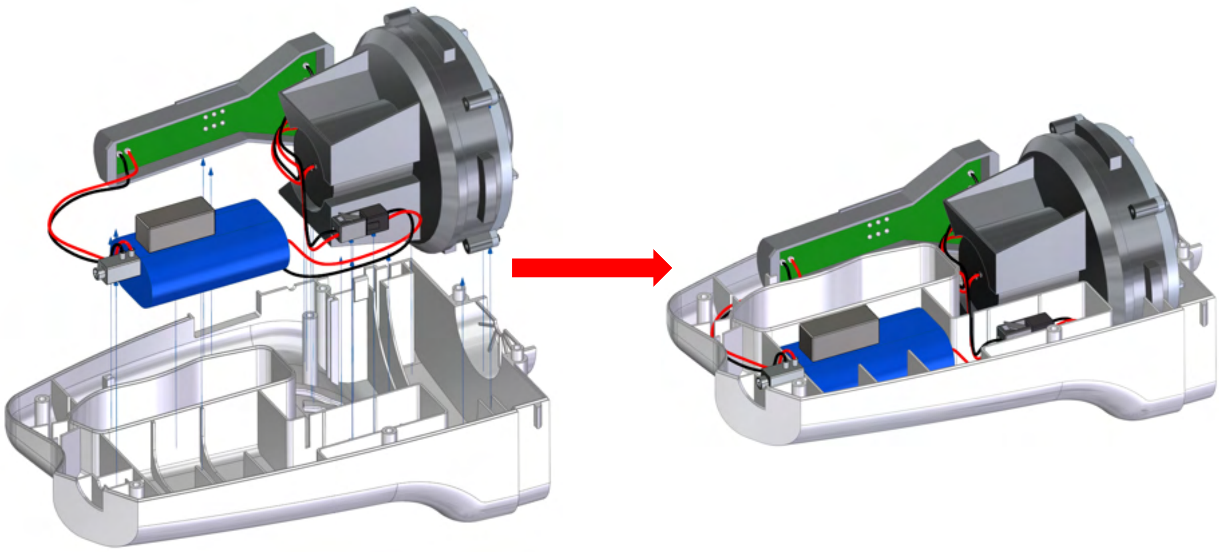


Figure 9. CAD image - Operation 5

The previously assembled unit is placed into the left half of the main housing (see Figure 9). This step requires careful positioning, as multiple components must align with corresponding slots and contours. The motor must be inserted with the correct rotational orientation, and all wires must be neatly arranged in designated cable channels to ensure that the second housing half can be mounted without interference or deformation.

Operation 6 – Installing Spring on Button

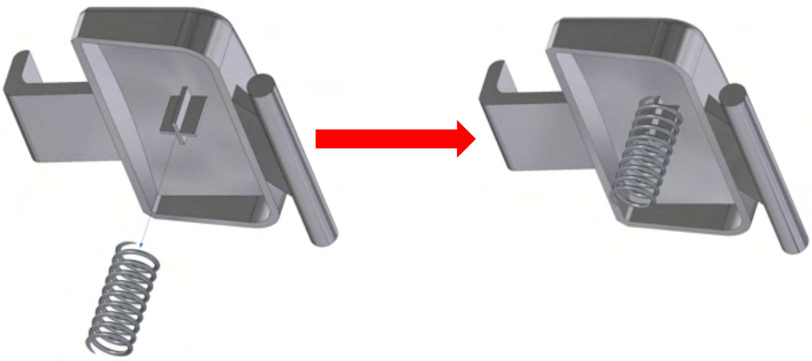


Figure 10. CAD image - Operation 6

A compression spring is inserted onto a cross-shaped post molded into the housing (see Figure 10).

Operation 7 – Assembling On/Off Switch

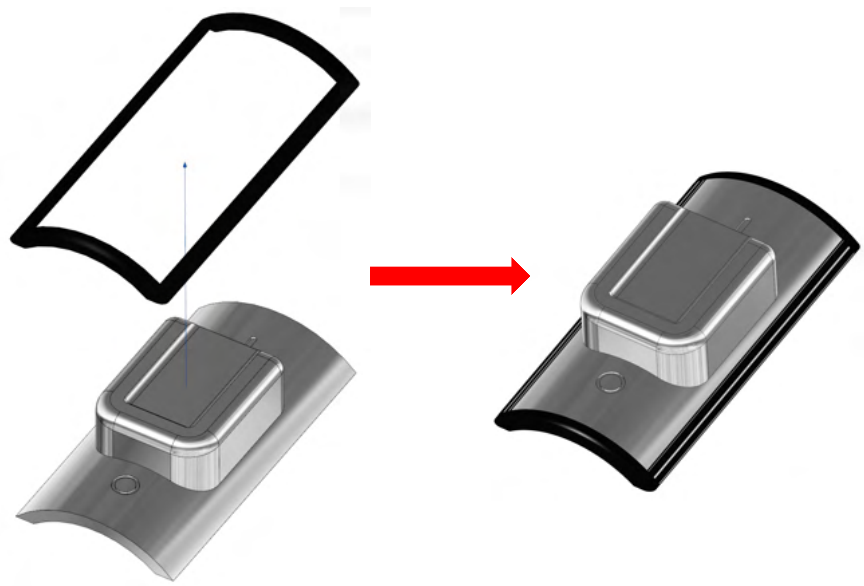


Figure 11. CAD image - Operation 7

The On/Off switch is fitted with a sealing ring to ensure dust-tight enclosure and consistent button response (see Figure 11).

Operation 8 – Inserting Push Button

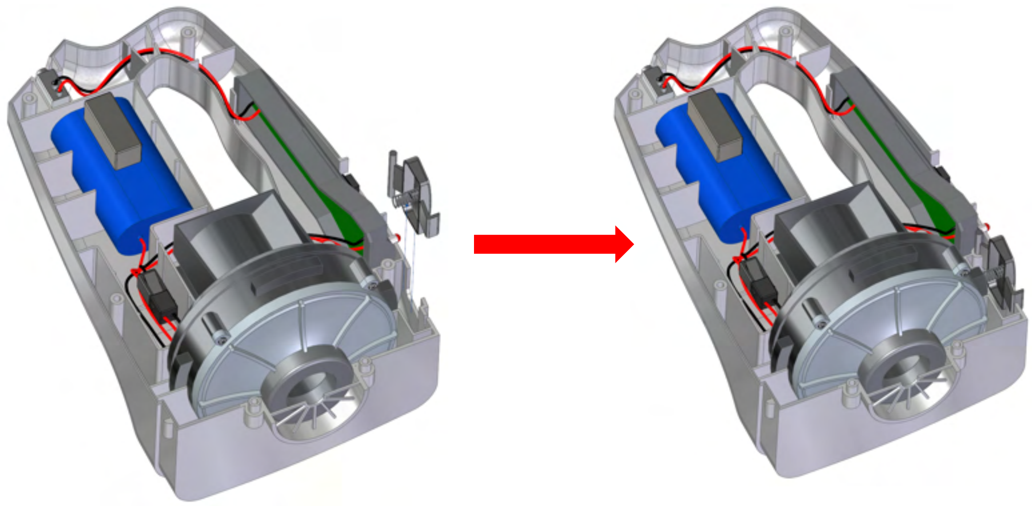


Figure 12. CAD image - Operation 8

The previously prepared push button, which is preassembled with a spring, is inserted into the housing (see Figure 12). During this step, the spring must be compressed slightly to fit within the housing geometry while retaining its preload.

Operation 9 – Installing On/Off Switch

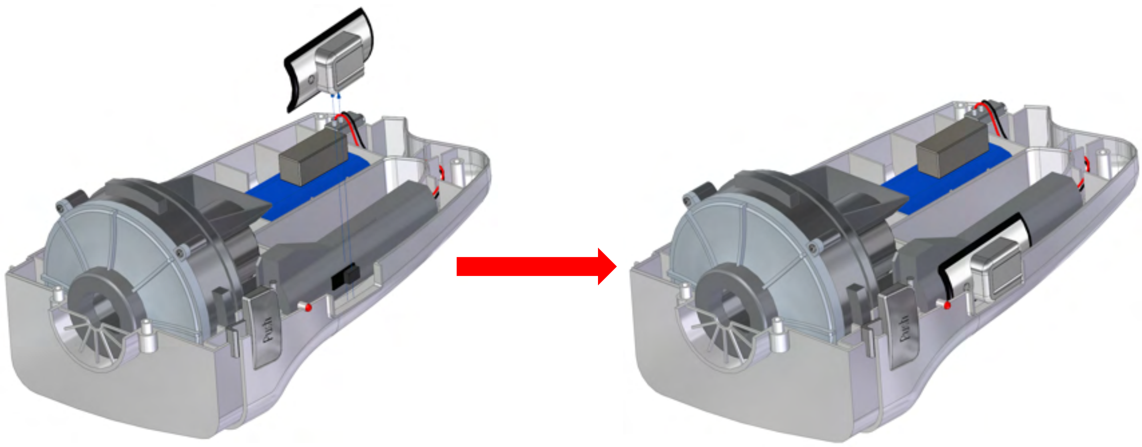


Figure 13. CAD image - Operation 9

The On/Off button is placed into its final position within the housing (see Figure 13). To achieve this, the control PCB must be slightly lifted so that the button can pass over and align correctly with the switch below.

Operation 10 – Closing Housing Assembly

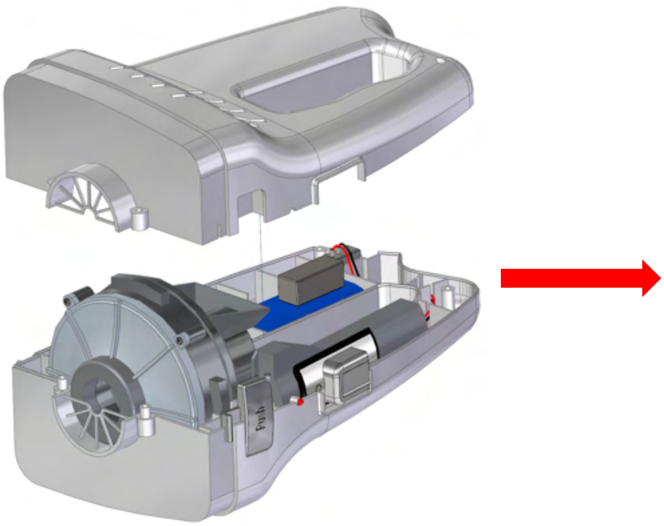


Figure 14. CAD image - Operation 10

After verifying that all internal components are correctly placed, the right half of the housing is mounted onto the left half, enclosing the internal assembly (see Figure 14).

Operation 11 - Fastening the Housing

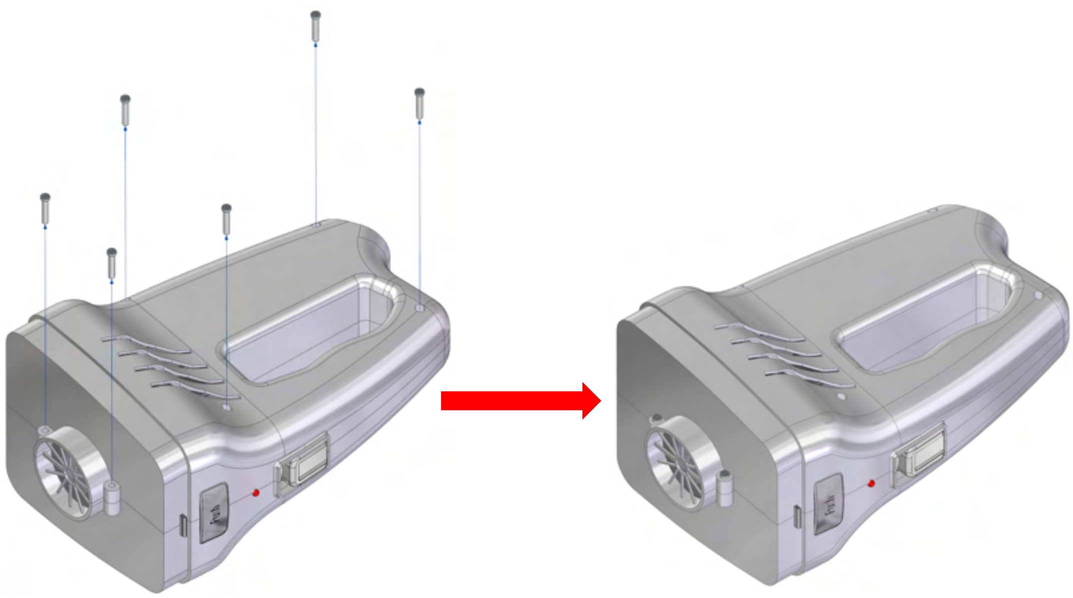


Figure 15. CAD image - Operation 11

The two halves of the housing are fastened using six screws (see Figure 15). This finalizes the enclosure of the main unit and ensures mechanical stability during operation and handling.

Operation 12 – Mounting Foam Filter

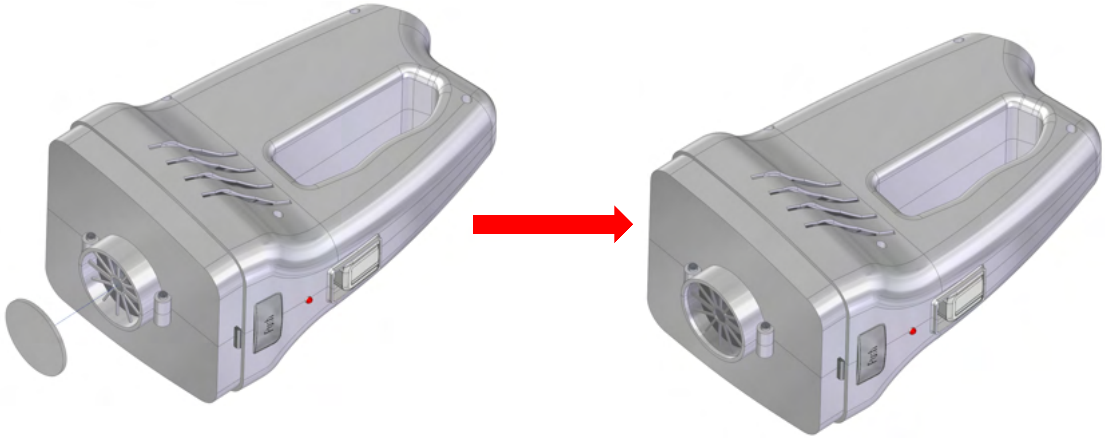


Figure 16. CAD image - Operation 12

A final filter element is attached to the hand unit (see Figure 16). This completes the main functional section of the handheld vacuum cleaner and prepares it for final external assembly.

Operation 13 – Inserting the Rubber Flap

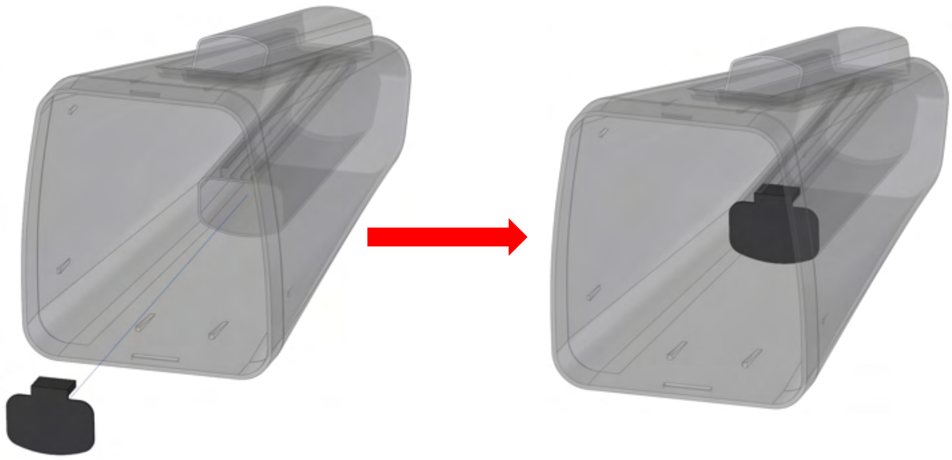


Figure 17. CAD image - Operation 13

The assembly of the external dust container (shell) begins with the placement of a rubber flap (see Figure 17). This component must be accurately aligned within its groove to ensure proper sealing and functionality.

Operation 14 – Installing Filter in the Holder

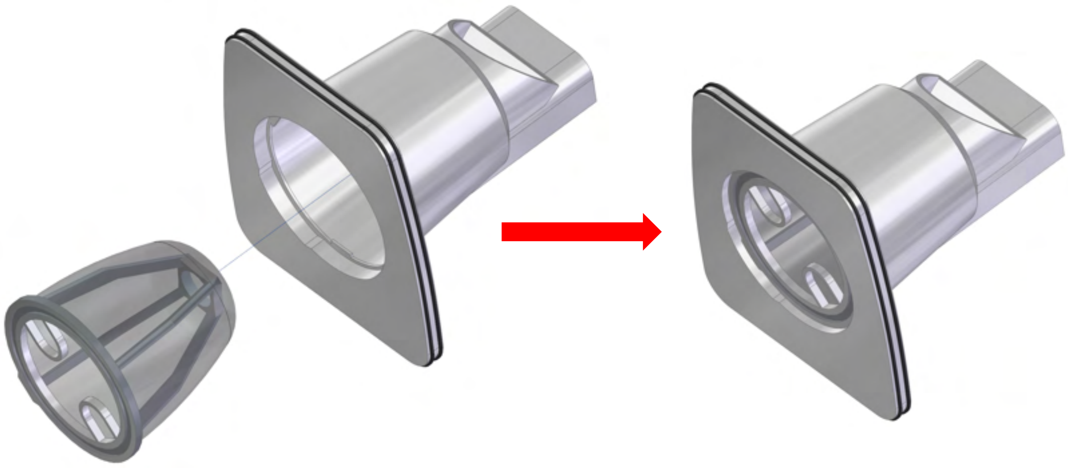


Figure 18. CAD image - Operation 14

The filter is inserted into the cylindrical holder and locked in place by twisting it clockwise until resistance is met and the locking tabs engage (see Figure 18).

Operation 15 – Joining Filter Module with the Shell

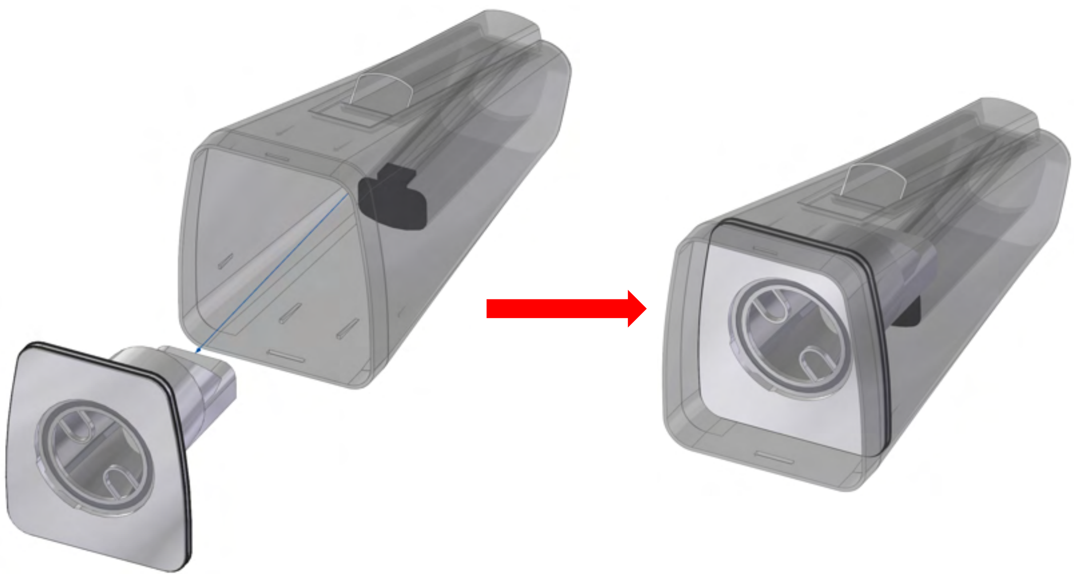


Figure 19. CAD image - Operation 15

The previously assembled filter unit is inserted into the shell (see Figure 19). It is essential that the filter holder is guided straight into position to avoid jamming or misalignment. Proper installation is confirmed when the holder rests fully against the mechanical stops inside the shell.

Operation 16 – Final Assembly of Shell and Hand Unit

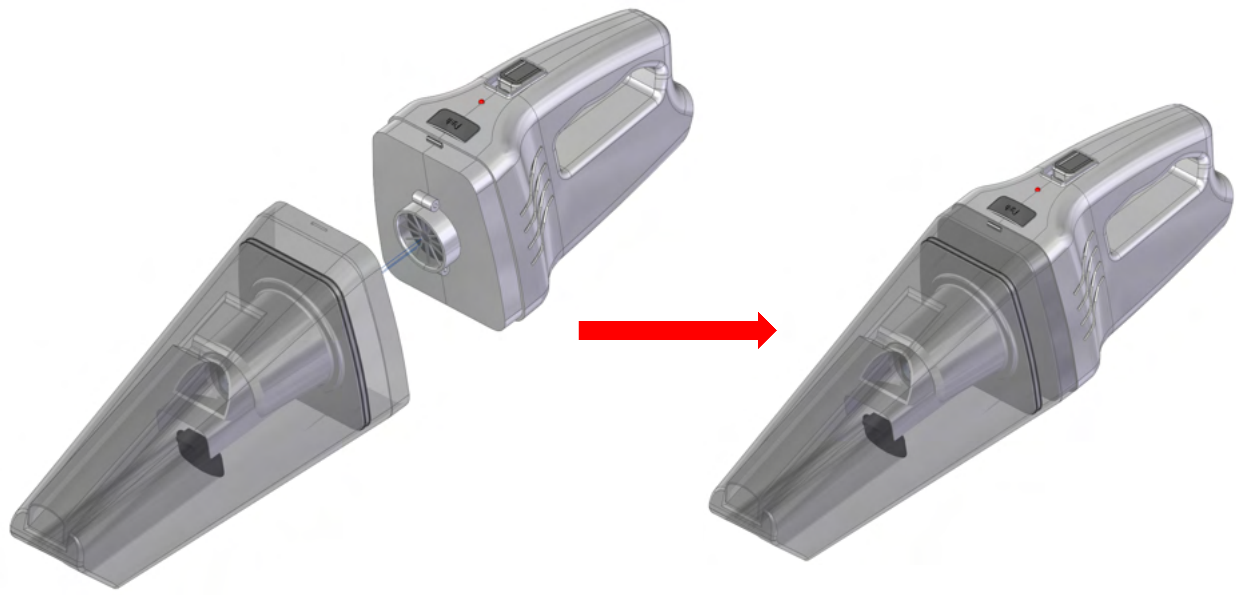


Figure 20. CAD image - Operation 16

In the final assembly step, the shell and the handheld unit are joined using a snap-fit mechanism (see Figure 20). A guiding rib on the bottom side of the handheld unit slides into a matching groove on the shell. The shell is then tilted upward, causing the upper snap feature to lock into place and securing the two components together.

4.2 Precedence Diagram

As part of the assembly process definition, a precedence diagram was developed to visualize the logical sequence and dependencies between the individual work elements involved in assembling the handheld vacuum cleaner (see Figure 21). The diagram illustrates the process flow from the initial to the final tasks, with directional arrows indicating precedence constraints between operations. Each task is represented by a node, and the estimated time required to complete the task is shown below it. This representation helps identify parallelizable tasks, critical paths, and sequencing logic, forming the basis for subsequent steps such as line balancing and workstation allocation.

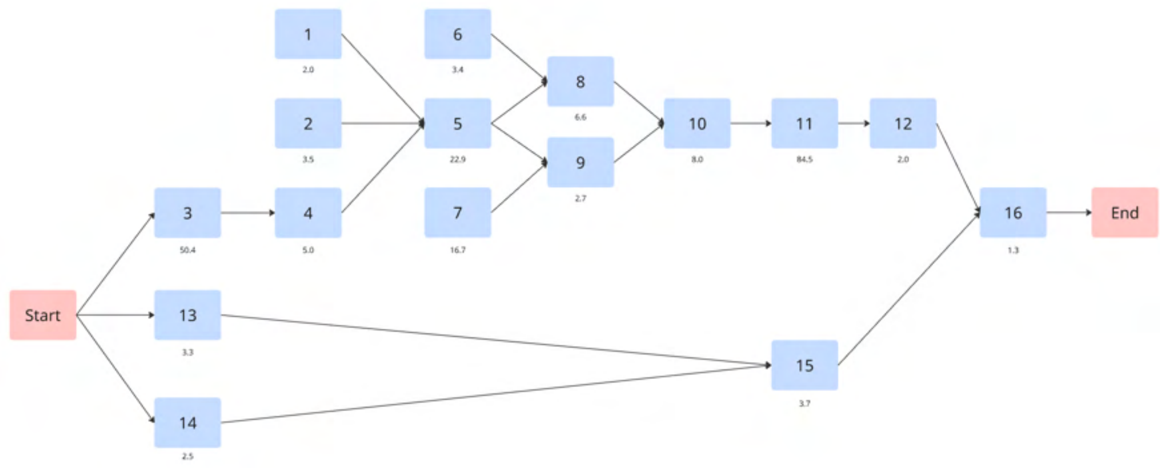


Figure 21. Precedence Diagram of the Assembly Operations

4.3 Liaison Sequence Diagram

The Liaison Sequence Diagram (LSD) illustrates the possible assembly paths of the handheld vacuum cleaner based on part dependencies and connection logic (see Figure 22). It provides a detailed view of how components interact and in which order they can be assembled, considering physical constraints and assembly feasibility.

The diagram reveals two valid starting points for the assembly process. One sequence begins with work element 3, while an alternative path starts with either work element 13 or 14. Apart from these variations in the entry and exit points, the overall assembly flow remains largely consistent. Based on principles covered in the course material, an optimized assembly sequence was defined. Alternative sequences that would unnecessarily complicate the process due to difficult access, misalignment risks, or additional repositioning were deliberately excluded.

The Liaison Sequence Diagram thus serves as a valuable tool for analyzing viable assembly paths and supports the development of an efficient, ergonomic, and time-effective assembly strategy.

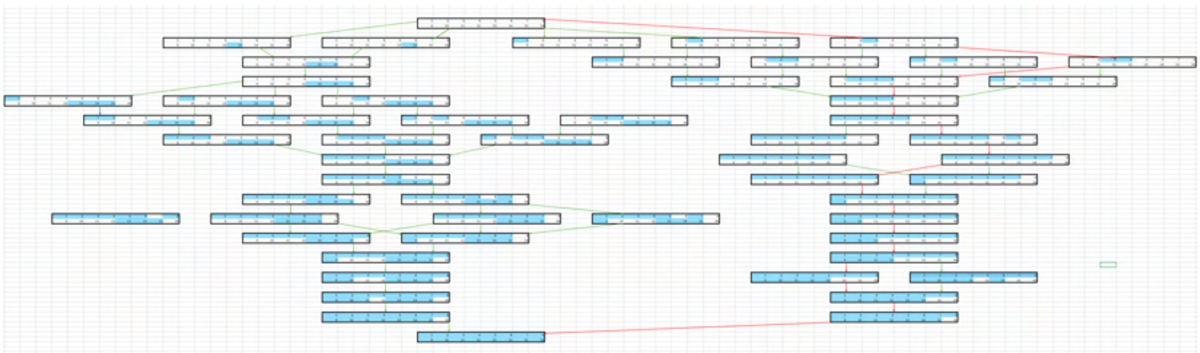


Figure 22. Liaison sequence diagram (Link to original document in the appendix)

4.3.1 Motivation of the best sequence:

- The housing was selected as the design base object due to its structural role and ability to support subsequent components during the assembly process. Additionally, the sequence emphasizes a top-to-bottom assembly direction, which reduces reorientations and supports gravity-assisted insertions.
- Start with work element 3 to enable work element 4 to be started and finishing one of the longest assembly tasks.
- Finish one of the sub-assemblies first and not start with the other independent sub assembly, therefore start with work element 13 and 14 after work element 12.
- When choosing between two independent work elements the work element that takes more time is first prioritized.

4.4 Evaluation of Assembly Process Time

To obtain representative data for the manual assembly process, the assembly time was measured under the following conditions. Four different individuals each performed the assembly sequence one time, resulting in a total of four measurements. This approach was chosen to account for variation in technique, speed, and handling across different operators. The manual runs included all relevant steps such as picking, orienting, and inserting the parts. All runs were performed on a standard table without fixtures or support tools. The parts were also pre-sorted on the table to support realistc picking times. By including multiple repetitions and participants, the dataset reflects a more realistic and reliable estimate of the average assembly time for the product and provides a more robust data basis for assembly line balancing. The measurements resulted in an average handling time of 57.8 seconds and an average insertion time of 160.3 seconds over the four runs. The detailed results from the measurement are shown in Figure 23 below.

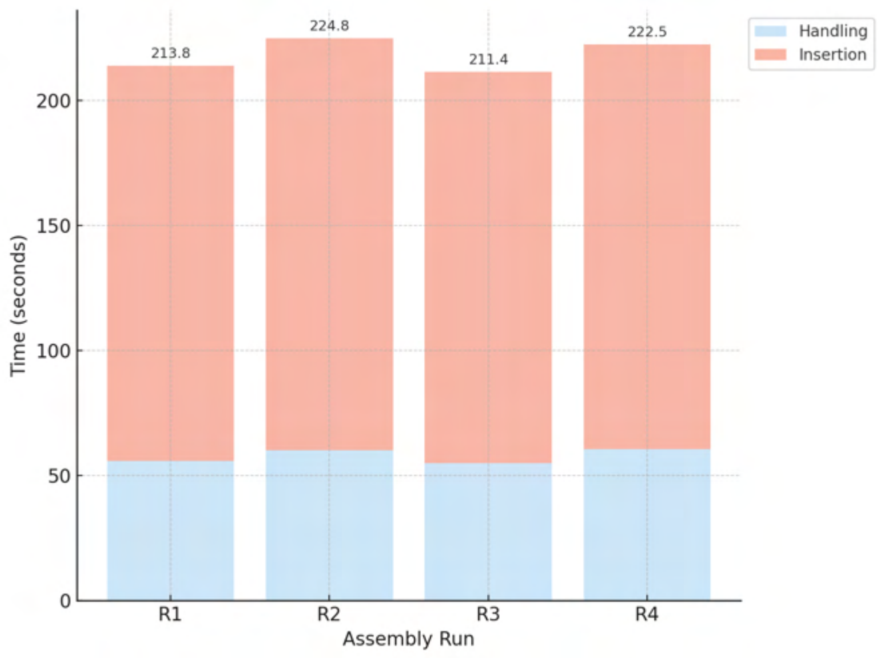


Figure 23. Results of the Performed Assembly Time Measurements

5 Assembly Line Balancing

5.1 Definition of a Production Scenario

The following production scenario provides the basis for the assembly line balancing and defines the estimated annual production volume for the handheld vacuum cleaner. The global handheld vacuum cleaner market in 2024 is valued at approximately $5.95 billion USD [2]. Assuming an average retail price of $80 USD per unit, this corresponds to an estimated 74.375 million units sold worldwide. To focus the production scenario, only specific European markets are considered: Sweden [3], Norway [4], Denmark [5], Finland [6], and Germany [7]. Together, these countries have a combined population of approximately 110.9 million, representing about 1.37% of the global population (8.1 billion in 2024) [8]. However, due to higher purchasing power in these countries, it is assumed that they account for 2.8% of global handheld vacuum unit sales. This results in an estimated 2,082,500 units sold annually within this region.

Assuming that our company positions itself as a mid-sized player in these markets with an estimated market share of 10%, the annual production volume to be planned for is 208,550 units.

5.2 Calculation of Required Number of Stations and Cycle Time

To balance the assembly line and ensure it meets the required output, several calculations were performed. The target hourly production rate calculated at 38.20 units per hour.

$$R_p = \frac{208{,}550\,\frac{units}{year}}{52\,\frac{weeks}{year}\cdot 15\,\frac{shifts}{week}\cdot 7\,\frac{hours}{shift}} = 38{,}20 \text{ products/hour}$$

From this, and assuming a line efficiency of 85%, the cycle time was determined to be 1.34 minutes per unit, which equals 80.4 seconds.

$$T_c = \frac{60\cdot 0.85}{54.95} = 1{,}34 \text{ minutes/unit}$$

The total task time required to assemble one unit is 218.35 seconds as evaluated during our time keeping in 4 assembly runs. Dividing this by the cycle time results in a theoretical requirement of 2.715 stations.

$$w^* = Minimum\ Integer \geq \frac{T_{wc}}{T_c} = 2{,}715$$

Since only whole numbers of stations are feasible in practice, a configuration with three stations was considered, providing each station with 72.78 seconds of working time.

$$min\ T_c = \frac{T_{wc}}{w} = \frac{218{,}35\ seconds}{3\ workstations} = 72{,}78 \text{ seconds}$$

To analyze the feasibility of this configuration, the service time was calculated by subtracting an estimated repositioning time of 5 seconds from the cycle time, resulting in 75.4 seconds available for actual task execution.

$$T_s = T_c - T_r = 80{,}4 \text{ [seconds]} – 5 \text{ [seconds]} = 75{,}4 \text{ [seconds]}$$

This leads to a repositioning efficiency of 93.78%, indicating high effective use of the available cycle time.

$$\text{Repositioning efficiency} = \frac{75{,}4\ [seocnds]}{80{,}4\ \text{[seconds]}} = 0.9378 \rightarrow 93{,}78\%$$

The balancing efficiency of the line was determined to be 96.53%.

$$\text{Balancing efficiency } \eta_b = \frac{T_p}{N \cdot T_{max}} = \frac{218{,}35\ [seconds]}{3 \cdot 75{,}4\ [seconds]} = 96{,}53\ \%$$

Taking this into account, the overall system efficiency which measures the proportion of time spent on value-adding activities was calculated to be 76.95%.

$$\eta = \eta_l \cdot \eta_r \cdot \eta_b$$

$$\eta = 0.85\ \times 0.9378\ \times 0.9653 = 0.7695 \rightarrow 76{,}95\ \%$$

Finally, based on all these performance indicators, the adjusted number of required stations was found to be approximately 3,01. This value was rounded up to a final requirement of 4 stations to ensure a robust and practical line configuration that can sustain the target output.

$$W = \frac{38.2\ \left[\frac{products}{hour}\right] \cdot 3.639\ \left[\frac{minutes}{unit}\right]}{60 \cdot 0.7695} = 3{,}01 \rightarrow 4 \text{ Stations}$$

Table 5 provides a summary of the calculation results presented in this chapter.

Table 5. Summary of Calculation Results

Value of interest	Abbreviation	Unit	Calculation approach	Result
Annual demand	D_a	pieces	Assumption based on available market data	208550
Hourly production rate	R_p	prod-ucts/hour	Use of formula	38,2
Number of shifts/week	S_w	shifts/week	Assumption based on production scenario	15
Number of hours/shift	H_sh	hours/shift	Assumption based on production scenario	7
Weeks in one year		weeks/year	Assumption based on production scenario	52
Cycle time	T_c	minutes/unit	Use of formula	1,34
Line efficiency	η_l	per-cent	Assumption based on production scenario	85
Sum of work element times	T_wc	sec-onds	Use of formula	218,35
Theoretical minimum number of workstations	w^*	quantity	Use of formula	3
Maximum available time for perform-ing tasks at a station	T_max	sec-onds	Use of formula	80,4
Time of repositioning	T_r	sec-onds	Assumption based on production scenario	5
Available service time for a station	T_s	sec-onds	Use of formula	75,4
Repositioning efficiency	η_r	per-cent	Use of formula	93,78
Balancing efficiency	η_b	per-cent	Use of formula	96,53
Overall system efficiency	η	per-cent	Use of formula	76,95
Total work content time	T_p	minutes/unit	Use of formula	3,35
Number of workstations (equal to w^*)	N	quantity	Use of formula	3
Actual number of station required	W	quantity	Use of formula	4

5.3 Application of Line Balancing Methods

5.3.1 Precdence Table

As a basis for the application of the line balancing methods, we first created a Precedence Table from the Precedence Diagram created in chapter 4.2 (see Table 6). This contains all the information required for the methods, including the work element, the process time T_e in seconds and the immediate predecessors, which represent the activities that must be complete before the respective work element can be started.

Table 6. Precedence Table as a basis for line balancing

Work element	T_e [sec]	Immediate predecessors
1	2	-
2	3,5	-
3	50,4	-
4	5	3
5	22,9	1, 2, 4
6	3,4	-
7	16,7	-
8	6,6	6, 5
9	2,7	7, 5
10	8	8, 9
11	84,5	10
12	2	11
13	3,3	-
14	2,5	-
15	3,7	13, 14
16	1,3	12, 15

5.3.2 Largest Canidate Rule

In the first step of the LCR method, we sorted the work elements by process time T_e in descending order. The results are shown in Table 7 below.

Table 7. Work elements sorted in decreasing order by Te

Work element	T_e [sec]	Immediate predecessors
11	84,5	10
3	50,4	-
5	22,9	1, 2, 4
7	16,7	-
10	8	8, 9
8	6,6	6, 5
4	5	3
15	3,7	13, 14
2	3,5	-
6	3,4	-
13	3,3	-
9	2,7	7, 5
14	2,5	-
1	2	-
12	2	11
16	1,3	12, 15

The sorted table was then used to assign the individual work elements to the stations. The method was followed which stipulates that the sum of the process times Te in a station must not exceed the service time Ts of 75.4. Using the LCR method, we obtained four required stations. It is important to note that stations three and four are parallel stations with identical assembly steps. The reason for this is that the process time of work element 11 is 84.5 seconds, which exceeds the service time and therefore makes assignment to a single station layout. Running these assembly steps at two stations in parallel results in the service time being undercut. The detailed results from the LCR method are shown in Table 8 below.

Table 8. Line balancing results from the LCR method

Station	Work element	T_e [sec]	Sum T_e, at station
1	3	50,4	
	7	16,7	
	4	5	72,1
2	2	3,5	
	6	3,4	
	13	3,3	
	14	2,5	
	15	3,7	
	1	2	
	5	22,9	
	8	6,6	
	9	2,7	
	10	8	58,6
3	11	84,5	
	12	2	

	16	1,3	87,8
4	11	84,5	
	12	2	
	16	1,3	87,8

In order to be able to evaluate the uniformity of the distribution of the work elements, the utilisation at the respective stations was calculated in the last step. To do this, the respective assembly time at the stations was divided by the service time. The results of the calculation are shown in the diagram in Figure 24. Station one has the highest utilisation of the four stations at 96%.

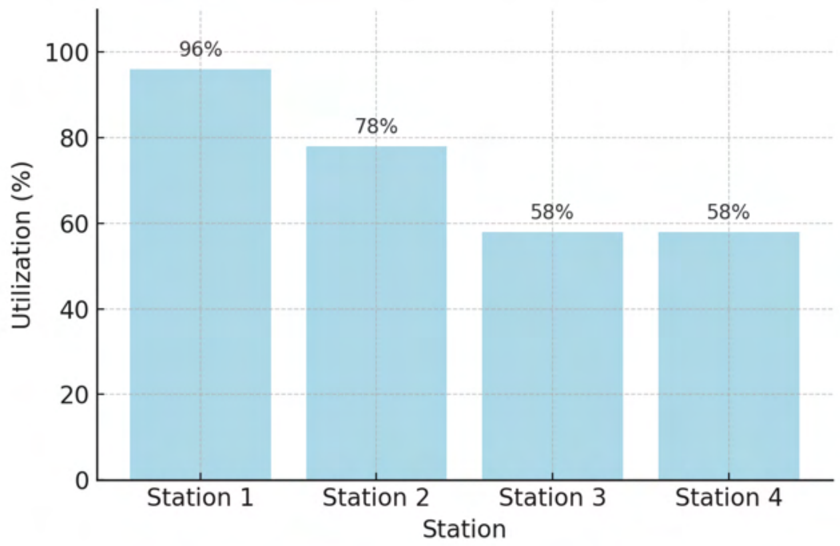


Figure 24. Station Utilization with the LCR method

5.3.3 Kilbridge and Wester Method

The Kilbridge & Wester method is a heuristic approach used to balance assembly lines. It helps create an efficient setup by grouping tasks based on their order and making sure each station stays within the allowed service time of 75,4 seconds. In this method, tasks are organized into columns based on their dependencies. For instance, tasks 3, 13, and 14 are all placed in column 1. Since there are no dependent tasks after them, tasks 13 and 14 can span from column 1 to column 6. Tasks 1, 2, and 4 fall into column 2, while tasks 5, 6, and 7 go into column 3. Tasks 8 and 9 are placed in column 4, task 10 in column 5, and task 11, which runs in parallel, is assigned to column 6. If task 11 were not a parallel operation, it would have exceeded the cycle time. The tasks that come after station 11 are also handled in parallel. A graphical overview is provided in Figure 25 below.

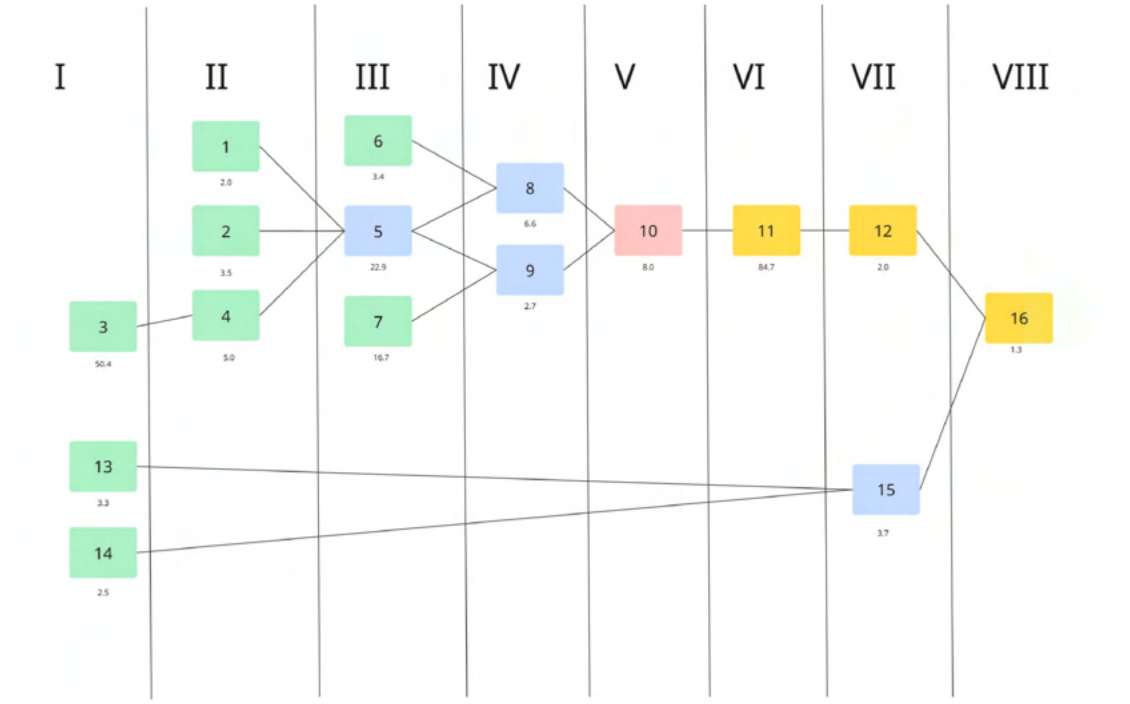


Figure 25. Division of assembly operations into columns

In the next step, the sums of the process times T_e per column were calculated. The work elements 13 and 14, which could theoretically be assigned to all columns between 1-6, were included in the sum of the first column. The sums of the process times in the columns are shown in Table 9 below.

Table 9. Process Times per column

Work element	Column	T_e [sec]	Sum of column T_e [sec]
3	1	50,4	
13	1,2,3,4,5,6	3,3	
14	1,2,3,4,5,6	2,5	56,2
1	2	2	
2	2	3,5	
4	2	5	10,5
5	3	22,9	
6	3	3,4	
7	3	16,7	43
8	4	6,6	
9	4	2,7	9,3
10	5	8	8
11	6	84,5	84,5
12	7	2	

15	7	3,7	5,7
16	8	1,3	1,3

In the final step, the individual work elements are assigned to the stations. In the Kilbridge & Wester method, the work elements from the front columns, i.e. starting with 1, are assigned first. The work elements from the columns behind are then assigned to the stations until the service time of 75.4 seconds is reached. The result shows that 4 stations are also required here, whereby stations 3 and 4 are stations in parallel operation. A detailed list of the results can be seen in Table 10 below.

Table 10. Results from Kilbridge & Wester method

Station	Work elements	T_e [sec]	Sum T_e, at station
1	3	50,4	
	1	2	
	2	3,5	
	4	5	
	6	3,4	64,3
2	5	22,9	
	7	16,7	
	8	6,6	
	9	2,7	
	10	8	56,9
3	11	84,5	
	12	2	
	13	3,3	
	14	2,5	
	15	3,7	
	16	1,3	97,3
4	11	84,5	
	12	2	
	13	3,3	
	14	2,5	
	15	3,7	
	16	1,3	97,3

The utilisation of the stations is therefore between 65 and 85%, with Station 1 achieving the highest utilisation at 85%. The bar chart in Figure 26 below shows the utilisation rates at the individual stations.

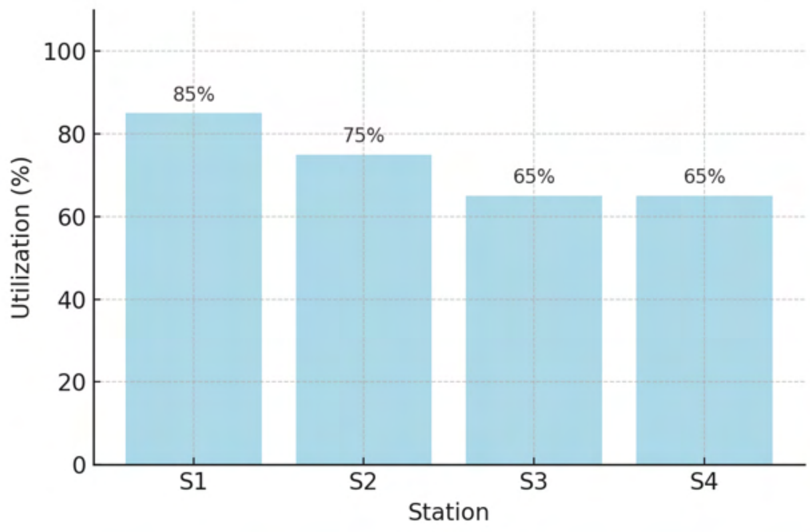


Figure 26. Station Utilization with the Kilbridge & Wester method

5.3.4 Ranked Positional Weight Method

In the first step, the RPW values were calculated using the positional weight method and then the table was sorted in descending order according to the RPW value. The RPW value results from the sum of the considered work element and all subsequent work elements that are dependent on the considered work element. The results are shown in Table 11.

Table 11. Assembly Operations sorted by RPW

Work element	RPW	T_e [sec]	Immediate predecessors
3	183,4	50,4	-
4	133	5	3
2	131,5	3,5	-
1	130	2	-
5	128	22,9	1, 2, 4
7	115,2	16,7	-
6	105,8	3,4	-
8	102,4	6,6	6, 5
9	98,5	2,7	7, 5
10	95,8	8	8, 9

11	87,8	84,5	10
13	8,3	3,3	-
14	7,5	2,5	-
15	5	3,7	13, 14
12	3,3	2	11
16	1,3	1,3	12, 15

Identical to the LCR method, the next step was to allocate the work elements to the stations. The RPW method also leads to four required stations. The third and fourth stations are also parallel stations for the same reason as in the LCR method. The detailed results are displayed in Table 12.

Table 12. Results from Ranked positional weights method

Station	Element	T_e [sec]	Sum T_e, at station
1	3	50,4	
	4	5	
	2	3,5	
	1	2	
	6	3,4	
	13	3,3	
	14	2,5	
	15	3,7	73,8
2	5	22,9	
	7	16,7	
	8	6,6	
	9	2,7	
	10	8	
	15	3,7	60,6
3	11	84,5	
	12	2	
	16	1,3	87,8
4	11	84,5	
	12	2	
	16	1,3	87,8

In terms of utilisation at the stations, the highest utilisation is at Station 1 with a utilisation rate of 98%. Figure 27 below shows the utilisation at all stations.

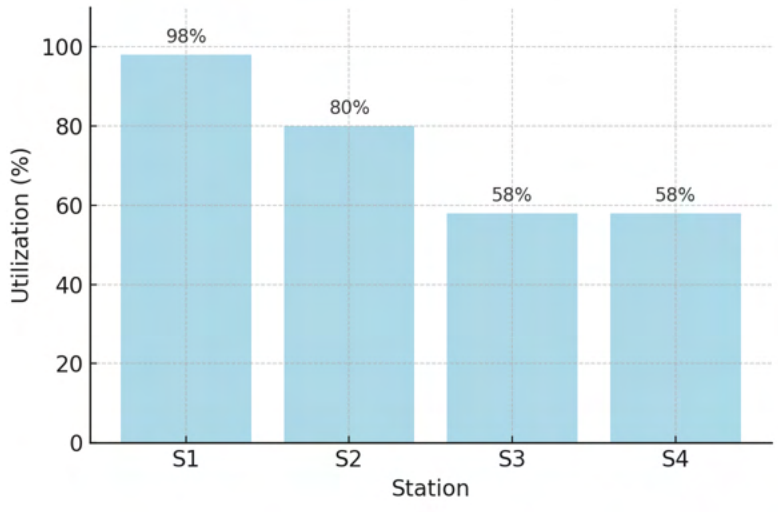


Figure 27. Station Utilization with the Ranked positional weights method

5.4 Comparison of the Results and Final Line Balancing

The Kilbridge & Wester method is the most suitable line balancing approach for our product. This method results in a well-balanced line, with all stations showing similar utilization rates. The highest utilization is 85%, which is relatively high but still allows for small errors while remaining within the service time. In contrast, the other two methods lead to utilization rates of 98% and 96% at station 1, creating a work environment with little to no margin for error. Since station 1 is the first in the sequence, downstream stations cannot build up a buffer and are heavily dependent on its performance. If scheduled maintenance is required, station 1 must operate below 96–98% utilization to accumulate a buffer, which is another reason for favoring the Kilbridge & Wester method. Additionally, if demand increases or the company enters a new market, there is a buffer of approximately 10–15% in available capacity. This provides flexibility and makes the company more resilient to demand fluctuations.

We are also aware that the parallel station setup, currently required due to the manual screwing process in work element 11, could potentially be eliminated by implementing electronic screwdrivers or robotic screw systems. For the final line balancing, we assumed that the process time could be halved to 42.25 seconds by using electric screwdrivers. Additionally, work element 6, initially assigned to station 1, was moved to station 2 to achieve a more balanced distribution of tasks along the assembly line. Based on this assumption and modification, the line balancing result shown in Table 13 was obtained.

Table 13. Result Final Line Balancing

Station	Work elements	T_e [sec]	Sum T_e, at station
1	3	50,4	
	1	2	
	2	3,5	
	4	5	60,9
2	6	3,4	
	5	22,9	
	7	16,7	
	8	6,6	
	9	2,7	
	10	8	60,3
3	11	42,25	
	12	2	
	13	3,3	
	14	2,5	
	15	3,7	
	16	1,3	55,05

6 Design for Assembly Analysis

6.1 DFA for Manual Assembly

Design for Assembly (DFA) for manual processes aims to evaluate and improve how easily and efficiently a product can be assembled by human operators. This section applies the Boothroyd method to assess the handheld vacuum cleaner, focusing on minimizing part count and reducing handling and insertion effort. By identifying theoretically unnecessary components and quantifying total assembly time, the analysis provides insights into structural simplifications and cost-saving opportunities, forming the basis for targeted design improvements.

6.1.1 Evaluation of Minimum Required Parts N_{min}

As part of the design for assembly evaluation, the handheld vacuum cleaner was analyzed to determine the theoretical minimum number of parts and to assess opportunities for simplification. The analysis followed standard DFA methodology, using three key criteria to evaluate whether each part is essential for product function or assembly:

1. Relative motion – the part must move relative to others.
2. Material or isolation requirements – the part must be made from a different material or serve a function such as insulation or vibration damping.
3. Assembly or disassembly constraints – the part must be separate to allow for correct assembly or access to other parts.

Each component was assessed against these criteria. Only parts meeting at least one criterion were considered necessary. Out of the full list of components, 11 parts were identified as essential, forming the theoretical minimum number of parts (N_{min} = 11). In addition to these criteria, the evaluation also considered functional criticality, for example how much each part influences product reliability, performance, or failure risk. Components such as the sealing ring (ensures vacuum tightness), the rubber flap (prevents backflow of debris), the on/off button and spring (central for safe operation), and the battery-to-motor connection (directly affects power delivery) were not only retained based on standard criteria but also due to their high impact on product function.

For DFA index calculation, the basic assembly time per part was assumed to be ta = 3 seconds. This time reflects the idealized average time for assembling a part with no handling, insertion and fastening difficulties. The detailed results from the analysis can be seen in Table 14. below.

Table 14. Evaluation of minimum required parts

Part	Criteria 1	Criteria 2	Criteria 3	Part Necessary (Yes/No)
Vacuum filter	False	True	False	Yes
Filter holder	False	False	True	Yes
Rubber flap	False	True	False	Yes
Shell	False	False	True	Yes
Spring	True	False	False	Yes
Foam rubber	False	True	False	Yes
On/Off button	True	False	False	Yes
Rubber ring On/Off Button	False	False	False	No
Release button	True	False	False	Yes
Left Side Housing	False	False	True	Yes
Right Side Housing	False	False	True	Yes
Turbine cover	False	False	False	No
Sealing ring	False	True	False	Yes
Circuit case	False	True	False	Yes
Motor + Circuit	False	False	False	No
Battery	False	False	False	No

6.1.2 Evaluation of t_{ma} and DFA Index Calculation

In the next step the required time to assemble the product in the current design has been evaluated (see Table 15.). The t_{ma} was determined using empirical data which were developed by Boothroyd. Each assembly operation is getting assigned one ID of the row and one ID of the column which then results in a time value. The total t_{ma} consists of handling times, insertion times and fastening times.

Table 15. Evaluation of tma

Operation ID	Handling Operation	Inserting Operation	Code Handling	Code Inserting	Est. Time Value Handling	Est. Time Value Inserting
1	Takes the turbine cover and orients it	Places the cover on the turbine	1_0	0_0	1,5	1,5
2	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
3	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
4	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
5	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
6	Takes the sealing from the bin and orient it	Place the sealing ring on the turbine cover	1_0	3_0	1,5	2
7	Grab the right housing and orient it	Place it in the fixture	8_3	3_0	5,6	2
8	Take the motor+circuit subassembly and orient them.	Place it in the right housing.	8_3	1_3	5,6	5
9	Grab the circuit case and orient it	Klick the circuit case on the circuit	3_0	3_4	1,95	6
10	Grab the battery and orient it	Place the battery in the housing	3_0	0_0	1,95	1,5
11	Grab the battery cable and orient it	Plug it into the cable connected to the curcuit	3_1	3_3	2,25	5
12	Takes the push button and orient it on the assembly surface		3_0		1,95	
13	Take the spring bring and orient it	Click the spring on the push button	0_0	3_0	1,13	2
14	Grab the button/spring assembly and orient it	Insert the button/spring assembly in the housing	3_0	3_1	1,95	5
15	Takes the on/off button and orient it on the assembly surface		3_0		1,95	

16	Take the rubber ring and orient it	Pull the rubber ring on the on/off button	0_0	3_0	1,13	2
17	Take the on/off button assembly and orient it	Insert the button/spring assembly in the housing	3_0	0_9	1,95	7,5
18	Takes the right handheld case from the bin and orients it	Places right side case to the left side case	3_0	2_0	1,95	2,5
19	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
20	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
21	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
22	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
23	Grab the foam rubber and orient it	Insert the rubber foam in the air duct	0_0	0_0	1,13	1,5
24	Grab the shell and orient it on the assembly surface		3_0		1,95	
25	Take the rubber flap and orient it	Insert the rubber flap in the shell	3_0	4_0	1,95	4,5
26	Takes the filter holder from the bin and orient it on the assembly surface		3_0		1,95	
27	Take the vacuum filter from the bin and orient it	Insert the vacuum filter in the filter holder	0_0	3_0	1,13	2
28	Take the vacuum filter assembly and orient it	Insert the vacuum filter assembly in the shell	3_0	3_0	1,95	2
29	Takes the shell assembly and orient it	Click the shell assembly on the upper side of the assembled housings	3_0	3_2	1,95	4
				Sum [seconds]	**55,81**	**96**

This results in a total t_{ma} of 151,81 seocnds which is the sum of the total handling time and insertion time. The insertion times also include the codes for fastening where applicable. Together with the N_{min}, t_a and the t_{ma} the DFA index can be calculated.

$$E_{ma} = \frac{N_{min} \times t_a}{t_{ma}}$$

$$= \frac{11 \times 3}{151,81} = 21,74\%$$

6.2 DFA for Automatic Assembly

In the Design for Automatic Assembly (DFA), we evaluated the assembly efficiency of a product at both part level and product level woth help of the Eskilander method.

6.2.1 Part Level Evaluation

Each individual component was assessed using 18 criteria related to automated assembly, based on a scoring system (see Table 16.). Key evaluation categories included:

- Necessity of the part for the assembly
- Handling aspects (e.g., orientation, gripping, center of gravity)
- Assembly operations (e.g., insertion, fastening, accessibility)

Table 16. Part Level Evaluation within DFA Automatic Assembly

Part description	Need to assemble part	Level of defects	Orientation	Non-fragile parts	Hooking	Center of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Hold assembled parts	Fastening method	Joining	Check/adjust	Sum
Vacuum filter	9	3	1	3	9	1	3	9	3	9	9	9	9	9	9	9	9	9	122
Filter holder	9	3	1	3	9	1	1	9	3	9	9	9	9	9	9	9	9	3	114
Rubber flap	9	3	1	9	9	1	1	9	9	3	9	3	9	3	9	9	9	9	114
Shell	9	3	1	1	9	1	1	9	1	3	9	9	9	3	9	9	9	9	104
Spring	9	1	1	9	1	1	9	9	9	3	9	9	3	3	9	9	9	9	112
Foam rubber	9	3	1	9	9	9	9	9	9	1	9	9	3	9	1	9	9	9	126
On/Off button	9	3	1	3	9	9	1	9	9	3	9	9	3	3	9	9	9	9	116
Rubber ring on/off button	1	3	1	9	9	9	3	9	9	1	9	9	3	9	9	9	9	9	120
Release button	9	3	1	3	9	9	1	9	9	3	9	9	3	3	9	9	9	9	116
Left housing	9	3	1	1	9	9	1	9	1	3	9	9	3	3	3	3	3	9	88
Right housing	9	3	1	1	9	9	1	9	1	3	9	9	3	3	3	3	3	9	88
Turbine cover	1	3	1	3	9	9	3	9	3	3	9	9	3	3	3	3	3	9	86
Sealing ring	9	3	1	9	9	3	3	9	9	1	9	9	9	9	9	9	9	9	128
Circuit case	9	3	1	3	9	9	1	9	3	3	9	9	9	9	9	9	9	9	122
Motor + Circuit	1	3	1	1	1	1	1	9	1	3	9	9	3	3	3	9	9	9	76
Battery	1	3	1	1	9	3	1	9	3	3	9	9	3	9	3	9	9	9	94
Screws	1	9	1	9	9	9	3	9	9	3	9	9	9	3	3	3	3	9	110
																			1836

$$Assembly\ Index_{Part} = \frac{Total\ Sum}{Parts\ \times Points} = \frac{1836}{17\ x\ 162} = 66.67\%$$

A total of 17 parts were analyzed, resulting in an accumulated score of 1836 out of a possible maximum based on the rating scale. The total number of DFA points awarded was 162, leading to a calculated assembly index of 66.67%. This indicates a relatively good potential for automated assembly, but with room for optimization, especially regarding parts like screws and battery mounting.

6.2.2 Product Level Evaluation

The complete product was evaluated (see Table 17.) as a whole using criteria such as:

- Number of parts
- Uniqueness of parts
- Existence of a proper base object
- Assembly direction
- Chains of tolerances
- Parallel operations

Table 17. Product Level Evaluation within DFA Automatic Assembly

Product Level	No of Parts	Unique Parts	Base Object	Design Base Object	Assebmly Directions	Parallel Operations	Chains of tolerances
Housing	9	1	9	1	9	9	3
Motor / Battery	9	1	9	1	9	1	3
Shell	9	1	9	1	9	1	3
Product	9	1	9	1	9	3	3

$$Assembly\ Index_{Product} = \frac{Achieved\ Points}{\max\ Points} = \frac{35}{63} \approx 55.56\%$$

From this, the sum relevant for the assembly index was 35 out of a maximum of 63, resulting in a product-level assembly index of 55.56%. This lower index suggests further optimization potential, especially in design standardization and simplification of assembly directions.

6.3 Suggestion of Design Improvements

6.3.1 Optimized Screw Selection – minimize part count

To support a more automation-friendly design, the use of cylinder hex head screws is recommended over crosshead screws. Their geometry offers better compatibility with standard automated screwdriver systems, as they allow magnetic pickup, reduce alignment issues, and minimize slippage. This leads to reducing fine motions during assembly such as precise alignment of tools which is key to improving automation speed and repeatability. Hex head screws reduce the need for these fine corrections and help avoid errors caused by tool-screw mismatch.

Moreover, implementing a single standardized screw type across the entire product minimizes tooling changes and simplifies feeding and gripping tasks. This aligns with the principles of high-speed automated assembly, which favor low product variety, consistent part orientation, and reduced changeover times. Fewer screw types also reduce inventory handling and increase assembly reliability.

6.3.2 Optimized Cabel Organization

Currently, the absence of cable guides causes inconsistent cable placement, increasing manual corrections during assembly and risking clamped wires. From an automation viewpoint, this results in unpredictable conditions for part insertion and housing closure, which automation systems struggle with due to their limited adaptability to variation.

Introducing molded cable guides or clips into the housing supports repeatable cable layouts, which is a prerequisite for reliable automation. Automated handling and insertion systems require defined paths and positions to avoid failures. Well-managed cable routing also simplifies the use of grippers, which can operate more efficiently in structured environments. Additionally, this reduces the need for visual checks or repositioning which impacts the cycle time positiviely.

6.3.3 Parts Modularization

A critical aspect of the current product design concerns the connection between the motor shaft and the turbine, as the turbine is pressed directly onto the motor shaft. From a disassembly and maintenance point of view, this solution is problematic. During the project, we were unable to separate the two components without applying excessive force or causing damage, which is why we decided to consider the assembly as one component. This design limits the possibility of carrying out repairs or replacing individual components in the event of a failure. Especially from the point of view of sustainability, where future products are expected to have a longer service life due to the ability to repair and replace parts, this connection contradicts the principles of modularity.

A more suitable strategy would be to introduce a detachable interface between the motor shaft and the turbine. The use of a clearance fit with fixation by a clamping bush would enable a secure mechanical connection and at the same time allow disassembly. These solutions would not only facilitate maintenance and potential repairs, but would also fulfil the objectives of the circular economy by allowing the reuse of still functional parts instead of replacing entire assemblies.

6.4 Impact of the Suggested Improvements

6.4.1 Impacts on DFA for manual assembly

As the changes to the screws described in chapter 6.3.1 have no influence on the manual assembly time evaluation, they are not taken into account in the new determination of the t_{ma}. The introduction of cable clips does have an effect on the insertion times for operations 8, 11 and 18. The effects of the optimisations are marked in Table 18. below.

Table 18. DFA manual assembly - Improvements evaluation

Operation ID	Handling Operation	Inserting Operation	Code Handling	Code Inserting	Est. Time Value Handling	Est. Time Value Inserting
1	Takes the turbine cover and orients it	Places the cover on the turbine	1_0	0_0	1,5	1,5
2	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
3	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
4	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5

5	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
6	Takes the sealing from the bin and orient it	Place the sealing ring on the turbine cover	1_0	3_0	1,5	2
7	Grab the right housing and orient it	Place it in the fixture	8_3	3_0	5,6	2
8	Take the motor+circuit subassembly and orient them.	Place it in the right housing.	8_3	0_3	5,6	3,5
9	Grab the circuit case and orient it	Klick the circuit case on the circuit	3_0	3_4	1,95	6
10	Grab the battery and orient it	Place the battery in the housing	3_0	0_0	1,95	1,5
11	Grab the battery cable and orient it	Plug it into the cable connected to the curcuit	3_1	2_3	2,25	4
12	Takes the push button and orient it on the assembly surface		3_0		1,95	
13	Take the spring bring and orient it	Click the spring on the push button	0_0	3_0	1,13	2
14	Grab the button/spring assembly and orient it	Insert the button/spring assembly in the housing	3_0	3_1	1,95	5
15	Takes the on/off button and orient it on the assembly surface		3_0		1,95	
16	Take the rubber ring and orient it	Pull the rubber ring on the on/off button	0_0	3_0	1,13	2
17	Take the on/off button assembly and orient it	Insert the button/spring assembly in the housing	3_0	0_9	1,95	7,5
18	Takes the right handheld case from the bin and orients it	Places right side case to the left side case	3_0	0_0	1,95	1,5
19	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
20	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
21	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
22	Pick a screw and orient it	Screw in the screw in the hole	0_1	9_2	1,43	5
23	Grab the foam rubber and orient it	Insert the rubber foam in the air duct	0_0	0_0	1,13	1,5
24	Grab the shell and orient it on the assembly surface		3_0		1,95	
25	Take the rubber flap and orient it	Insert the rubber flap in the shell	3_0	4_0	1,95	4,5

26	Takes the filter holder from the bin and orient it on the assembly surface		3_0		1,95	
27	Take the vacuum filter from the bin and orient it	Insert the vacuum filter in the filter holder	0_0	3_0	1,13	2
28	Take the vacuum filter assembly and orient it	Insert the vacuum filter assembly in the shell	3_0	3_0	1,95	2
29	Takes the shell assembly and orient it	Click the shell assembly on the upper side of the assembled housings	3_0	3_2	1,95	4
				Sum [seconds]	**55,81**	**92,5**

$$E_{ma} = \frac{N_{min} \times t_a}{t_{ma}}$$

$$= \frac{11 \times 3}{148,31} = 22,25\%$$

The new DFA index after the optimisations is 22.25%, so the improvement is relatively small from the original 21.74%. Nevertheless, based on the experience gained during the project, we are of the opinion that the introduction of cable clips/cable guides significantly facilitates assembly and brings advantages that exceed the percentage difference.

6.4.2 Impacts on DFA for automatic assembly

The suggested design improvements also positively affect the product's suitability for automatic assembly. Reducing the number of unique fasteners and standardizing components simplifies tool requirements and lowers the complexity of automated handling. Improved cable routing and part modularization enhance accessibility and alignment, making robotic insertion and joining more reliable. As a result, the overall DFA index for automatic assembly increases only slightly to 66.69 %. However, the identified improvement potential exceeds what is reflected by the relatively modest increase in the assembly index.

Table 19. DFA automatic assembly - Improvements evaluation

Part description	Need to assemble part	Level of defects	Orientation	Non-fragile parts	Hooking	Center of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Hold assembled parts	Fastening method	Joining	Check/adjust	Sum
Vacuum filter	9	3	1	3	9	1	3	9	3	9	9	9	9	9	9	9	9	9	122
Filter holder	9	3	1	3	9	1	1	9	3	9	9	9	9	9	9	9	9	3	114
Rubber flap	9	3	1	9	9	1	1	9	9	3	9	3	9	3	9	9	9	9	114
Shell	9	3	1	1	9	1	1	9	1	3	9	9	9	3	9	9	9	9	104
Spring	9	1	1	9	1	1	9	9	9	3	9	9	3	3	9	9	9	9	112
Foam rubber	9	3	1	9	9	9	9	9	9	1	9	9	3	9	1	9	9	9	126
On/Off button	9	3	1	3	9	9	1	9	9	3	9	9	3	3	9	9	9	9	116
Rubber ring on/off button	1	3	1	9	9	9	3	9	9	1	9	9	3	9	9	9	9	9	120
Release button	9	3	1	3	9	9	1	9	9	3	9	9	3	3	9	9	9	9	116
Left housing	9	3	1	1	9	9	1	9	1	3	9	9	3	3	3	3	3	9	88
Right housing	9	3	1	1	9	9	1	9	1	3	9	9	3	3	3	3	3	9	88
Turbine cover	1	3	1	3	9	9	3	9	3	3	9	9	3	3	3	3	3	9	86
Sealing ring	9	3	1	9	9	3	3	9	9	1	9	9	9	9	9	9	9	9	128
Circuit case	9	3	1	3	9	9	1	9	3	3	9	9	9	9	9	9	9	9	122
Motor + Circuit	1	3	1	1	1	1	1	9	1	3	9	9	3	3	9	9	9	9	82
Battery	1	3	1	1	9	3	1	9	3	3	9	9	3	9	9	9	9	9	100
Screws	1	9	1	9	9	9	3	9	9	3	9	9	9	3	3	3	3	9	110
																			1848

$$Assembly\ Index_{Part} = \frac{Total\ Sum}{Parts\ \times Points} = \frac{1848}{17\ x\ 162} = 66.69\%$$

7 Workstation and Assembly Line Design

7.1 Material Handling

Efficient material handling plays a critical role in enabling a streamlined and reliable assembly process. In our proposed concept, all components required for a given workstation are provided as dedicated kits (Figure 28). Each kit includes only the parts necessary for the specific set of operations performed at that station. This method supports lean principles by reducing local stock levels, preventing overhandling, and simplifying part identification.

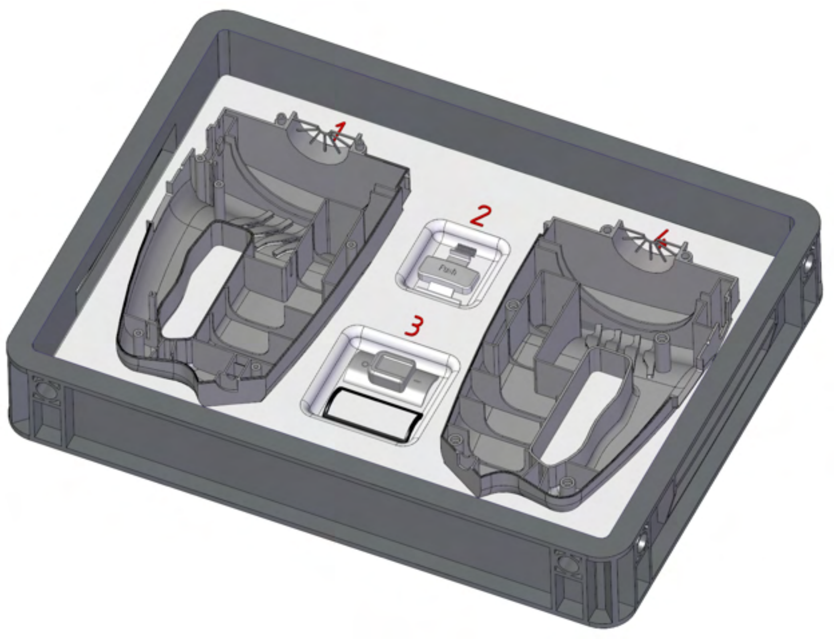


Figure 28 Station 1 - Material Box

The kits are organized in standardized euroboxes, which are widely used in industrial logistics and compatible with existing material supply systems. Each box contains a custom insert shaped to match the negative geometry of the included parts. These inserts hold the components securely in place, protect them during transport, and provide visual clarity during the picking process.

To support proper sequencing, each position in the insert is labeled with a number that reflects the assembly sequence. This assists operators in maintaining the correct process flow and reduces the risk of errors or omissions. The structured presentation of parts also supports efficient operator training and contributes to consistency in manual operations.

By combining kit-based provisioning, geometry-specific inserts, visual sequencing, and digital guidance, this material handling concept supports core manufacturing objectives such as reduced cycle time, ergonomic improvement, and standardized work. The standardized physical arrangement of parts within the kits not only improves manual handling but also establishes a solid basis for future automation and robotic part picking.

7.2 Fixtures

Fixtures are a fundamental element in ensuring consistency, precision, and repeatability during manual assembly processes. By providing defined positioning and mechanical support, fixtures reduce operator dependency, improve ergonomic conditions, and minimize variability between different assembly runs or operators. In particular, they play a key role in stabilizing parts during fastening operations, aligning components for accurate assembly, and ensuring process reliability without requiring complex measuring or adjustment tasks.

Beyond their direct impact on product quality and cycle time, well-designed fixtures also simplify operator training and support the implementation of standardized work procedures. In the context of this project, dedicated fixtures were developed to assist with critical steps in the vacuum cleaner assembly, especially those involving screwdriving and click-fit operations. Their integration into the workstation layout contributes to the overall efficiency and robustness of the assembly line.

Fixture 1 – Housing

The first fixture was developed to support the secure and repeatable positioning of the left housing shell during several key assembly steps (see Figure 29). It is fixed directly to the workstation and provides a defined reference for inserting internal components and completing the enclosure of the product. The fixture is essential in operations where precise alignment is required to prevent misplacement or mechanical interference between parts, especially during the integration of the Motor/Battery/PCB subassembly (see 2.2.2 Subassemblies), push button, and On/Off button, as well as during final closure and fastening of the housing.

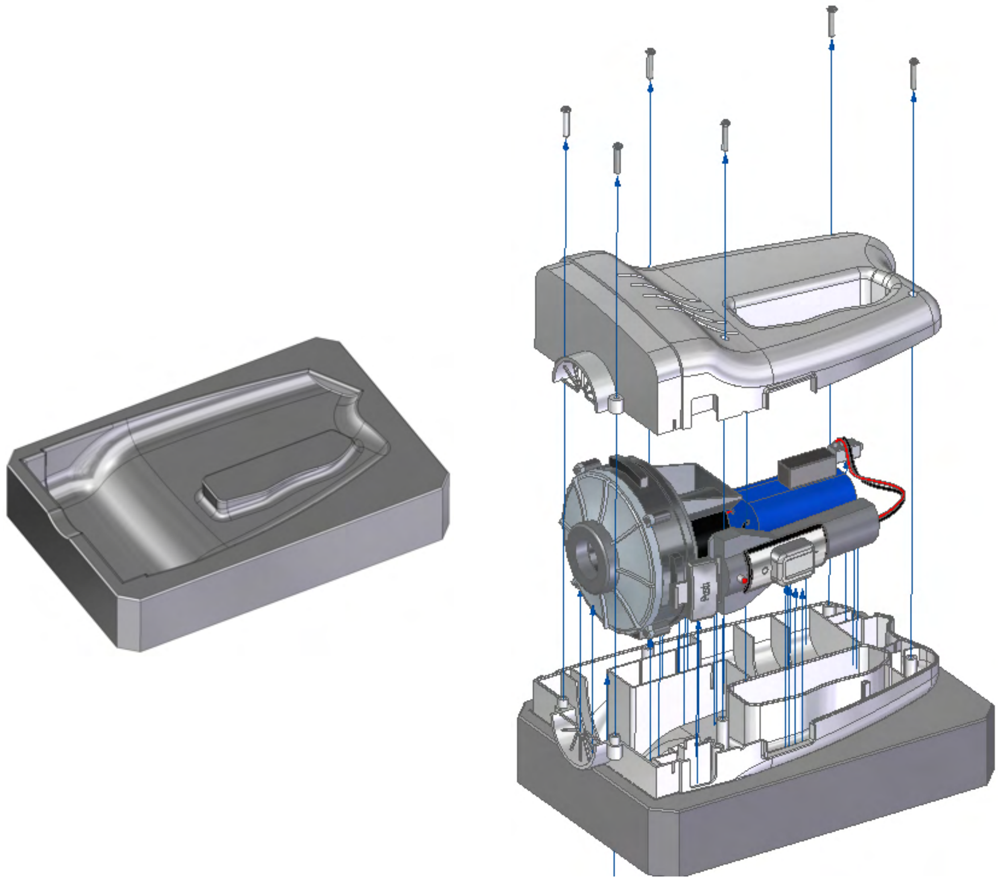


Figure 29 Fixture Housing

A central design feature of the fixture is its ability to maintain the housing in a stable orientation that aligns the screw axes vertically. This not only facilitates ergonomic screwdriving but also ensures process consistency when using torque-controlled tools. In earlier stages, such as the insertion of the motor and wiring assembly, the fixture allows the operator for precise cable management and delicate placement of components. The fixture geometry also helps to avoid unwanted stress or deformation on sensitive features.

In addition to improving positioning accuracy and process stability, the fixture contributes to cycle time reduction by eliminating the need for constant manual readjustment. Its clear part interface simplifies the operator's workflow and supports intuitive use, even for less experienced personnel. Moreover, the standardized placement it provides, lays the foundation for future automation, as the fixture defines consistent starting conditions for robotic gripping, insertion, or fastening operations.

Fixture 2 – Motor Subassembly

Fixture 2 was developed to stabilize the motor subassembly during the screw fastening process (see Figure 30). It is positioned directly on the workbench and designed to accommodate the geometry of the preassembled motor module, which includes the turbine, control board, and associated wiring. The fixture holds the unit in a fixed position, allowing precise vertical access to the screw locations on the turbine cover.

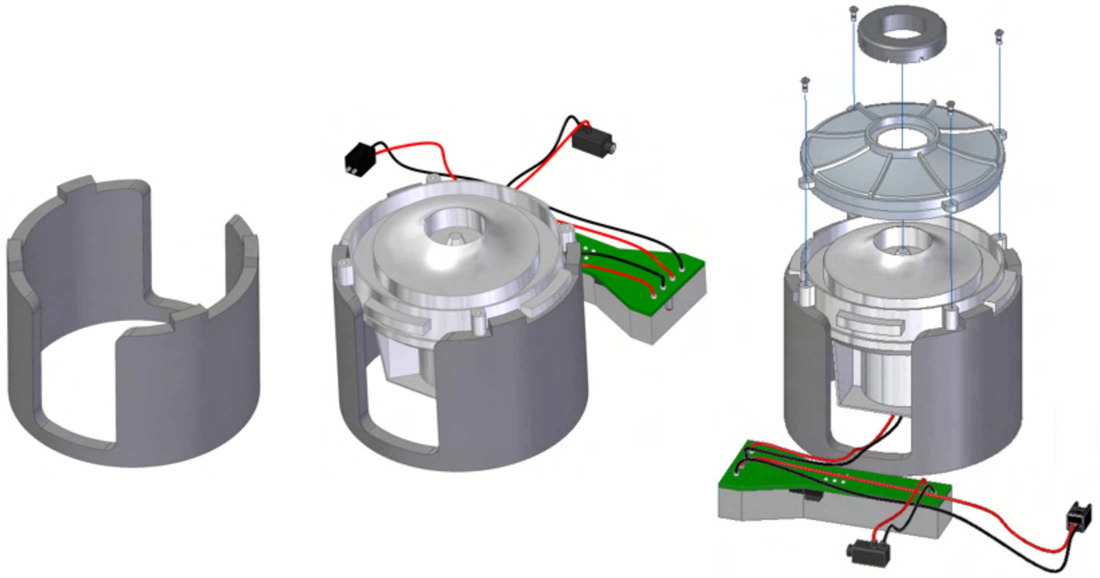


Figure 30 Fixture Motor

Its form-fitting design prevents rotation and movement of the component during assembly, which is essential for maintaining alignment and preventing damage to sensitive electrical connectors. The fixture also enables the controlled use of an electric screwdriver, which ensures consistent torque application and reduces operator fatigue during repetitive tasks.

By supporting vertical screw insertion and securing the component from multiple sides, the fixture reduces the risk of tool slippage and improves overall process reliability. Its robust and open design allows for easy loading and unloading while keeping all functional surfaces accessible. This makes it particularly useful in series production or when assembly tasks are distributed across multiple shifts.

In addition to improving the ergonomics and accuracy of the screwdriving operation, Fixture 2 serves as a preparation step for potential future automation, as it defines a repeatable clamping position that could be replicated by robotic tooling.

Fixture 3 – Platina Case

Fixture 3 was developed to support the insertion of the control PCB into its designated housing component (see Figure 31, note that the other parts of the subassembly are hidden due to improved clarity). Due to the tight fit and the sensitivity of the electronic part, a stable fixture is essential to ensure uniform pressure distribution during the pressing operation. The fixture holds the case securely in place and guides the PCB into the correct position, preventing tilting or misalignment during insertion.

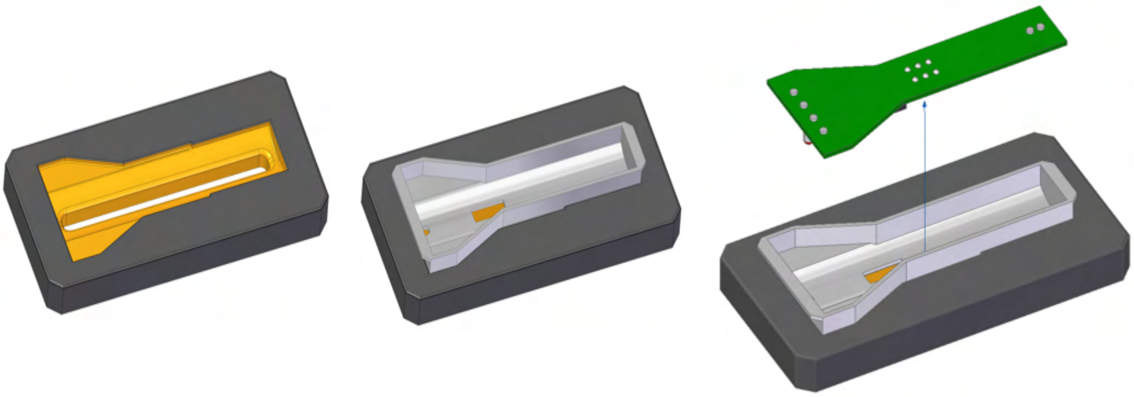


Figure 31 Fixture PCB case

Without proper support, there is a risk of the PCB jamming or being damaged by uneven forces, especially at the connector points and along the board edges. The fixture geometry ensures that the component is fully supported across its critical contact surfaces while leaving sufficient access for manual or tool-assisted pressing.

By standardizing the alignment and providing mechanical guidance, this fixture reduces the likelihood of assembly errors, such as incorrect orientation or incomplete seating. It also improves process repeatability, shortens cycle times, and enables consistent quality across multiple assembly cycles.

In future setups, the defined positioning established by this fixture may also serve as a reference point for semi-automated pressing tools or integration into a modular workstation concept.

Fixture 4 – Shell

Fixture 4 is used to hold the shell component in a vertical position during assembly (see Figure 32). This orientation is particularly important when inserting the filter, as the components must remain properly aligned to avoid jamming, resulting in increased assembly time. The fixture ensures that the shell remains stable and centered throughout the process, allowing the operator to press the filter and the rubber flap into place with even force and full control.

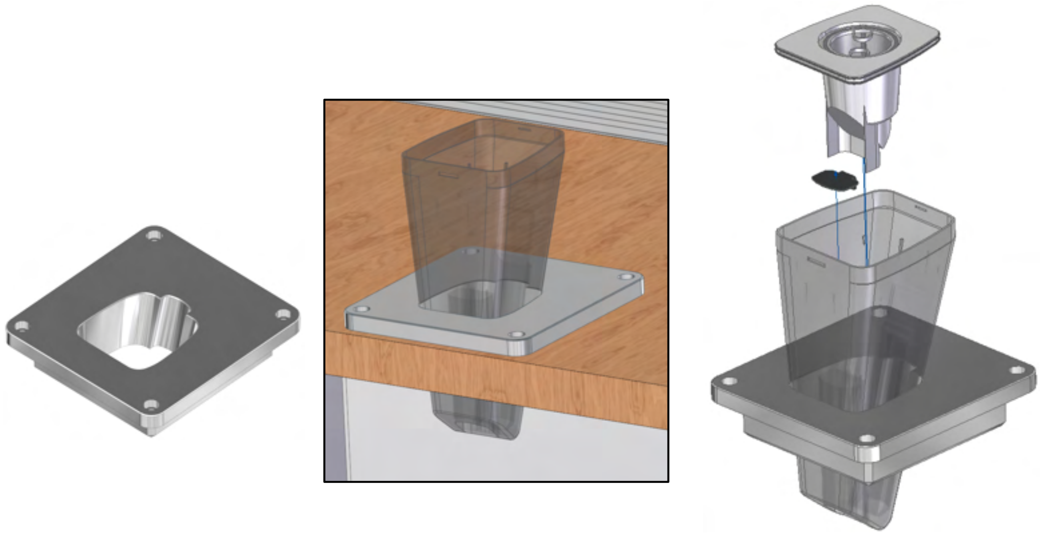


Figure 32 Fixture Shell

The fixture is integrated directly into the workbench and features an opening that allows the shell to extend downward through the tabletop. This design enables the operator to work from a natural seated or upright position without having to reach over the component. As a result, the fixture offers a clear ergonomic benefit by reducing shoulder and wrist strain and allowing for more relaxed, precise handling.

Its downward-facing cavity geometry also simplifies gravity-assisted assembly and improves accessibility to the filter interface. In addition to enhancing operator comfort, this fixture contributes to overall process stability and standardization, while also leaving open the option for future integration of guided pressing tools or semi-automated filter insertion.

7.3 Assembly Line

The assembly line concept for the handheld vacuum cleaner consists of three workstations arranged in a linear configuration (see Figure 33). The workstations are connected via a roller conveyor, allowing smooth transfer of workpieces between stations.

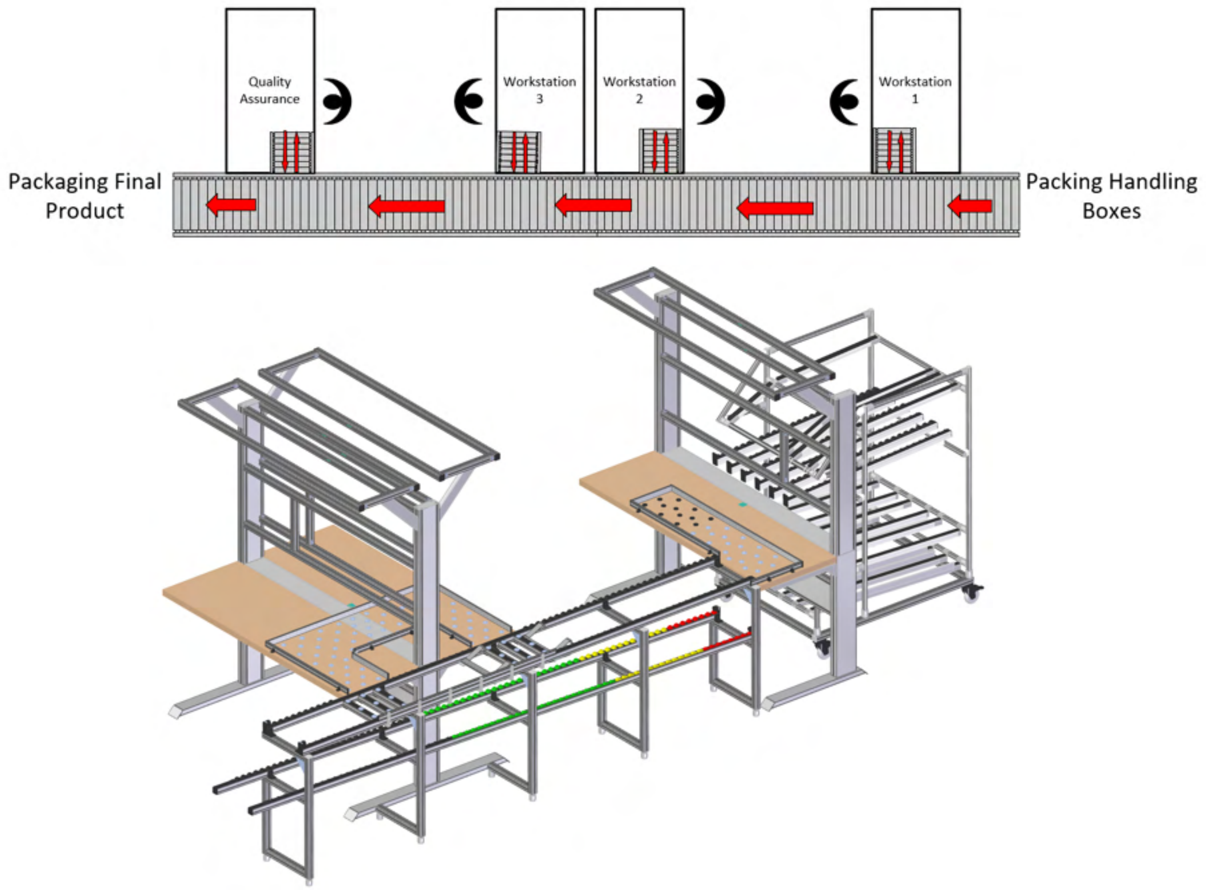


Figure 33 Assembly Line

The Euroboxes are pre-packed in advance and contain all required components except for screws, which are stored separately in ergonomically positioned grip trays at each station. After the assembly steps at a given station are completed, the Eurobox is pushed further along the conveyor to the next station. This setup minimizes manual handling, shortens transfer times, and ensures a clear and structured material flow. Each Eurobox is transported between stations using the conveyor and can be pulled directly onto the workbench for processing.

Each workstation is equipped with height-adjustable workbenches, allowing operators to adapt the working height to their individual ergonomic needs, thus reducing physical strain and promoting healthy posture.

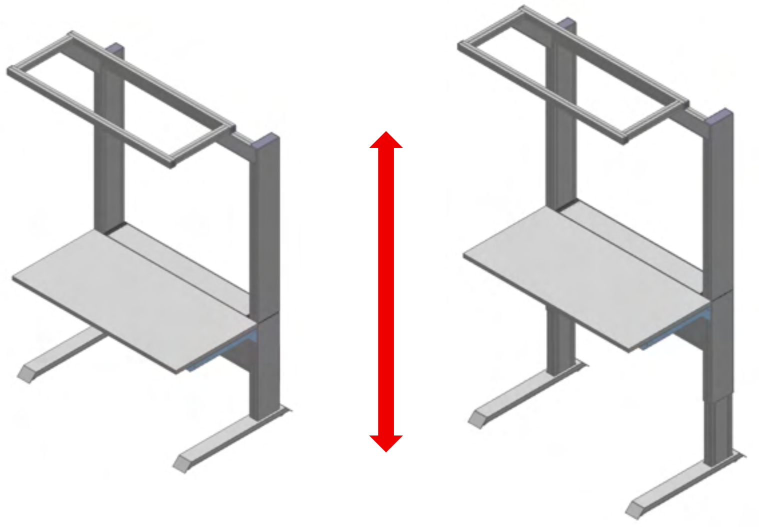


Figure 34 Height adjustable workbench

In line with modern ergonomic standards, the workstation layout follows the reach zone principle, which defines optimal ranges for frequently, occasionally, and rarely accessed tools and materials. Frequently used items are placed within the primary reach zone (close to the body and shoulder height), while less frequently needed items are stored further away. This minimizes overreaching, twisting, and fatigue during repetitive tasks.

To further support efficiency and quality, visual management elements are integrated into the workstation design. These include clear labeling of containers, color-coded components, and visual indicators for work instructions, torque settings, and quality checks. Additionally, the line is equipped with adequate LED lighting, ensuring sufficient and uniform illumination of the entire workspace.

All screw fastening tasks are performed using EC (Electronic Control) screwdrivers (see Figure 35). These tools provide consistent torque control and emit an acoustic signal once the correct number of screws has been applied, supporting process reliability and operator feedback. We use a tightening torque of 0.8 Nm for our screws, based on the recommendations of STANLEY® Engineered Fastening (accord. to [14]), which suggest applying approximately 65% of the strip torque as a safe seating torque for threaded fasteners in plastic components. This value is also in line with common industrial guidelines for thread-forming metal screws used in thermoplastic housings.

Figure 35 TensorStraight Cable Screwdriver Tensor ES from Atlas Copco [15]

The EC drivers are suspended above the workstation via a spring balancer, which significantly reduces wrist strain and prevents the tool from obstructing the workspace. This suspension system allows the screwdriver to return automatically to its neutral position, keeping the work surface clear and improving overall ergonomics.

Figure 36 Spring Balancer EC driver [16]

Altogether, this assembly line setup supports standardized, efficient, and ergonomic manual production. It also forms a strong foundation for potential future integration of semi-automated operations and process monitoring systems.

7.3.1 Consideration of automatic Assembly

The possibility of automating parts of the assembly process for the handheld vacuum cleaner was carefully evaluated. While automation can provide substantial benefits in large-scale, repetitive production environments, it was determined that full automation is not appropriate or beneficial for the core assembly tasks of this product. Several key factors led to this conclusion.

First, many of the components involved in the assembly are extremely small and lightweight. These characteristics pose significant challenges for robotic gripping systems, which would require highly sensitive and costly end-effectors to handle such parts without damaging them. Furthermore, several components feature irregular freeform geometries that do not allow for reliable, repeatable gripping or placement without customized fixtures or complex vision systems.

Additionally, certain tasks, such as the insertion of the motor assembly into the left housing (Operation 5), inherently require human dexterity and real-time adjustments. These operations involve cable routing, alignment across multiple axes, and feedback-based force application, which are currently difficult to replicate with industrial robots without implementing advanced human-robot collaboration systems. Such systems would introduce complexity, cost, and space requirements that are disproportionate to the assembly volumes involved.

Another critical consideration is the lack of significant cycle time advantages through automation in this specific context. Manual assembly with guided tools and standardized fixtures already achieves sufficient throughput with high reliability. Automating these processes would not result in a meaningful reduction in assembly time, especially when considering the setup, maintenance, and potential downtimes of robotic equipment.

For these reasons, the use of robots was limited to the start and end of the line, where they can provide clear logistical benefits. Robots may be used to load and unload euroboxes onto the conveyor system and to transfer finished products into storage or packaging units. These tasks are repetitive, have low complexity, and can be handled efficiently with a parallel gripper setup and basic line tracking.

Other arguments against full automation include the relatively low batch sizes, the need for flexibility in product variants, and the risk of long changeover times when switching between different configurations. Manual assembly remains the most robust, adaptable, and economically viable solution under the current production conditions.

8 Economic Analysis

8.1 Manual assembly

LH is calculated by multiplying 200 Kr cost per hour according [9] and with additional fees including insurance and holiday pay etc. the cost for the company is 50% extra per hour this gives: 200 Kr * 1,5 = 300 Kr per hour.

L_H = 300 Kr

A$ = $300 \times 2000 = 600\,000$ Kr

Q = 208.550 [Production volume]

From line balancing

N is already calculated within T from the line balancing.

Cycle time for one station	80,4 s
Stations	3
T	$3 \times 80{,}4 = 241{,}2\ s$

Worker hr_{year}= 2080

#People = $\frac{T \times Q}{hr_{year} \times 3600} = \frac{241{,}2 \times 208\,550}{2\,080 \times 3\,600} = 6{,}7$

$COST_{Unit\ Manual} = \frac{A_{dollar} + \#People}{Q} = \frac{600\,000 \times 6{,}7}{208\,550} = 19{,}3\ Kr$

8.2 Automated assembly

S$: SCARA robot which is easy to use for most stations' costs between 250000 and 100000 Kr, take a cost of 500000 Kr per robot [10]. Because our company produce low budget product we assume the robot and the cell with additional transport method is included in the price of 500 000 Kr per robot.

Additional investment are for grippers and sensors for all stations. Assuming use of optical sensors for all stations. A reliable optic sensor cost 3000 Kr [11]. Assuming jaw gripper for each station cost around 23000 Kr [12].

Another cost that automated factories most account for is licenses to run the factory such as robotics /automation license. One example is SAP unattended automation for small companies cost around 65000 Kr [13]. Our company may need a bit bigger system so assumption is about 125000 Kr.

These costs accumulated to 526 000 Kr per station

N = 16 [parts/unit]

S$ = $N \times 526\,000 + 125000 = 8\,541\,000$

$f_{AC} =$ 0,1 [fraction of machine cost/year]

Q = 208 550 [units/year]

$C_{UNIT\ FIXED} = \frac{0{,}1 \times 8\,000\,000}{208\,550} = 3{,}84\ Kr$

8.3 Additional costs

Material costs:

Assuming 50 Kr around 17% of the cost of buying the vacuum cleaner.

Warehouse and extra fixed costs:

Cost of a warehouse according to Jamie Jacobs (2020) is 250 000 Kr.

250000/Q = 250000/208550 = 1,2 Kr per product.

Cost of electricity and logistics, assuming 10 Kr per product.

Cost of buying the vacuum cleaner from Clas Ohlson is 280 Kr.

8.4 Multi-scenario cost analysis

This chapter will compare three different scenarios with ROI on one year and also break even based on how much the company sells the hand held vacuum cleaner to Clas Ohlson. Manual investment is 80000 Kr for four work stations and 50000 Kr for the quality control based on the work stations in chapter 7 this totals in 130000 Kr investment. Automatic investment is 8541000 Kr based on chapter 8.2 and have the quality control for 50000 Kr this totals in 85910000 Kr investment.

8.4.1 Scenario 1

In the first scenario, our company sells the product for 100 Kr to Clas Ohlson. Profit/product for manual assembly is around 19,5 Kr and for automatic assembly it is around 35 Kr. Break even for manual assembly are 6675 pieces and automatic assembly 247 500 pieces. ROI is calculated for every month, which is seen in Figure 37.

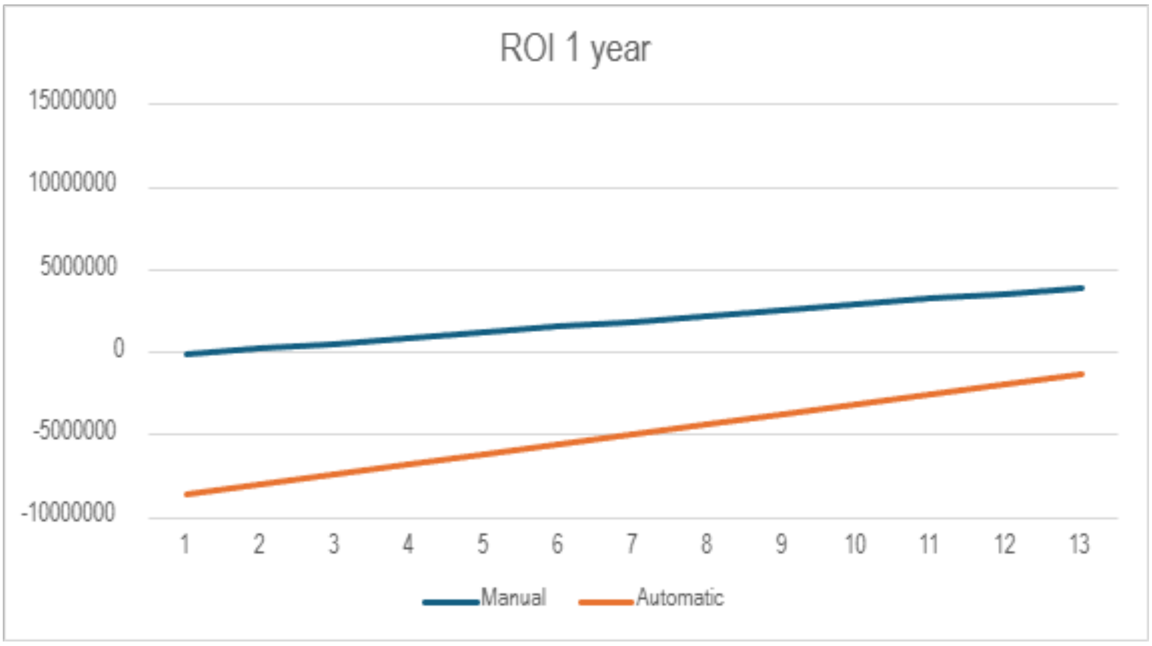


Figure 37. ROI 1 year after initial investment for scenario 1

Number 1 in graph shows initial investment without production and number 13 shows ROI after 1 year. Manual assembly gave result 3 930 000 Kr, automated assembly gave results –1 353 000 Kr.

8.4.2 Scenario 2

In the second scenario, our company sells the product for 140 Kr (Clas Ohlson gets 100% profit when selling). Profit/product for manual assembly around 59,5 Kr and for automatic assembly it is around 75,5 Kr. Break even for manual assembly are 2185 pieces and for aautomatic assembly 115000 pieces. ROI is calculated for every month, which is seen in Figure 38.

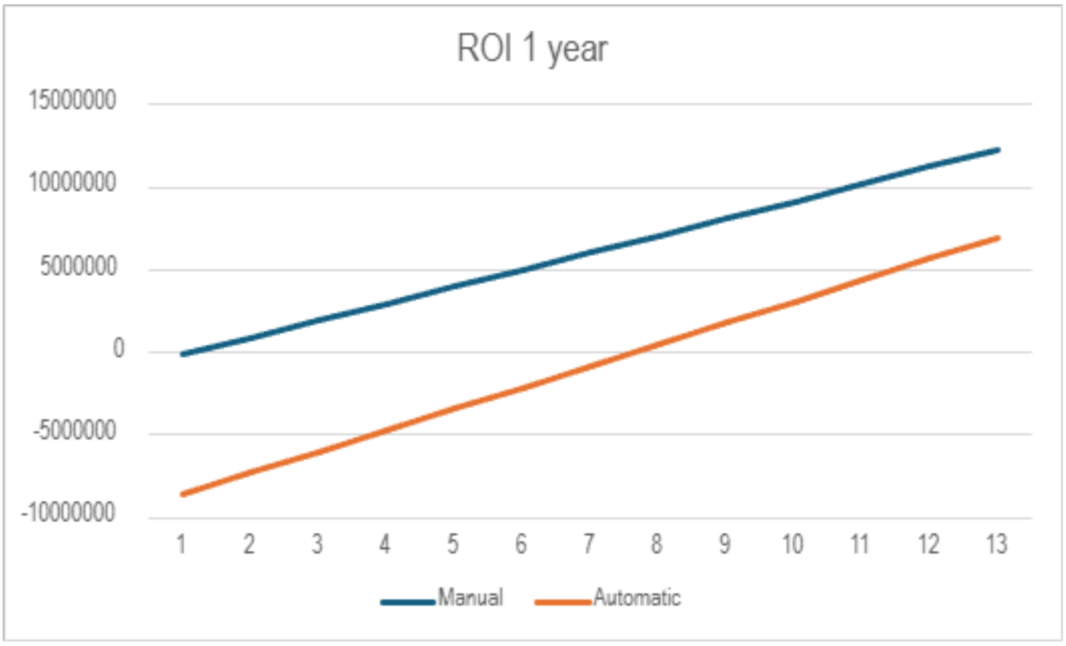


Figure 38. ROI 1 year after initial investment for scenario 2

Number 1 in graph shows initial investment without production and number 13 shows ROI after 1 year. ROI after 1 year are 12 273 000 Kr and for automatic assembly are 6 998 000 Kr.

8.4.3 Scenario 3

In the third scenario, our company sells the product for 85 Kr. Profit/product for manual assembly around 4,5 Kr and for automatic assembly it is 20 Kr. Break even for manual assembly are 29000 products and for automatic assembly, 436 000 products. ROI is calculated for every month, which is seen in Figure 39.

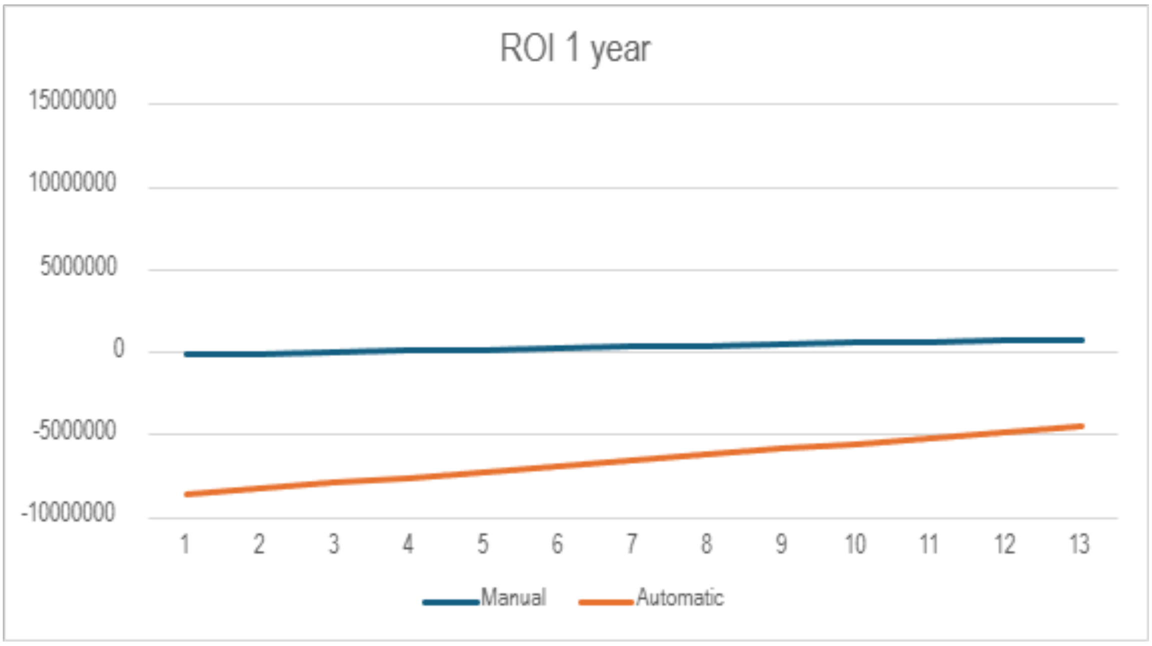


Figure 39. ROI 1 year after initial investment for scenario 3

Number 1 in graph shows initial investment without production and number 13 shows ROI after 1 year. ROI after 1 year for manual assembly 802 650 Kr and for automatic assembly – 4 482 000 Kr.

8.4.4 Cost per unit

Manual cost is the same regardless of demand however when demand changes cost for automation per unit decreases exponentially and this is calculated while demand is 118500, 148550, 178550, 208550, 238550, 268550 and 298550. The cost per unit for automation was 7,2, 5,75, 4,78, 4,09, 3,58, 3,18, 2,86. These values indicate that the cost per unit was done right because of the exponential cost per unit decrease. Both manual and automatic assembly cost per unit is shown in Figure 40.

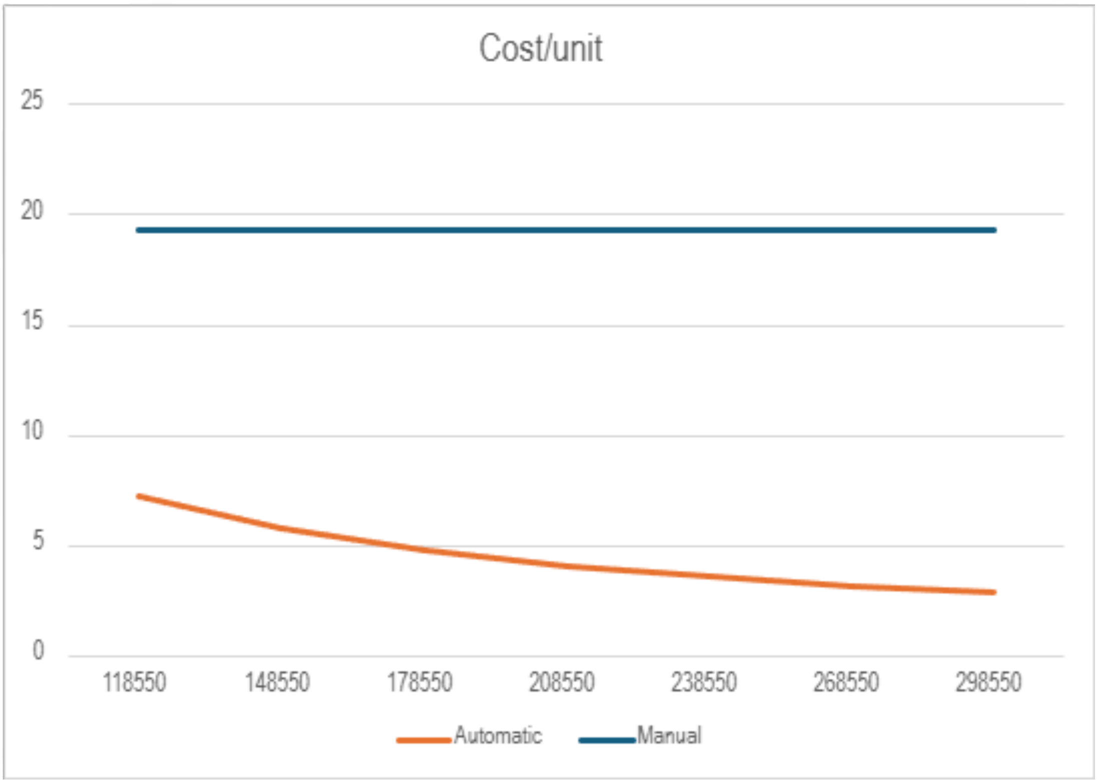


Figure 40. Cost per unit when demand changes

8.5 Comparison

In all three scenarios, the investment in automatic assembly is too high to get a better ROI than manual assembly. All of these show that four manual stations and workers together is faster to break even in all these scenarios than the automatic assembly. In all of these scenarios manual assembly is better than automatic assembly even though cost per unit is higher for manual assembly than automatic. It is very hard to get loans or investment for 8,591 million Kr compared to 130000 Kr and manual assembly is much easier to set up. Our economic comparison indicates strongly that manual assembly should be used. The automated assembly need long time to pay off and is also harder to regulate if demand fluctuates.

9 Conclusion

This project presented a comprehensive analysis and structured redesign of the assembly process for a commercially available handheld vacuum cleaner. Throughout the course of the project, our team applied a broad spectrum of assembly engineering methods, from CAD modeling and function mapping to assembly sequence development, line balancing and design, Design for Assembly (DFA) analysis and finally a economical analysis.

Starting from a detailed CAD reconstruction, we built a complete part catalogue and exploded view that served as the foundation for defining subassemblies and understanding interdependencies between components. A functional decomposition and liaison diagram enabled us to visualize structural relationships and define a logical and manufacturable assembly sequence. This sequence was refined using a precedence diagram and validated through a Liaison Sequence Diagram (LSD), with critical process steps supported by custom-developed fixtures.

Our time study provided realistic input data for line balancing, which we performed using three established methods. The Kilbridge & Wester method yielded the most robust and balanced configuration. We defined a manual assembly line with three primary workstations and a fourth auxiliary station, optimized for ergonomic working conditions, standardized part flow, and operator efficiency. Fixtures and EC screwdrivers were implemented to improve repeatability, reduce strain, and support torque-controlled fastening.

In parallel, a Design for Assembly analysis was conducted at both manual and automated levels. While the current design offers reasonably good DFA values, our assessment revealed concrete areas for improvement. We proposed optimizations such as standardized fasteners, modularization of critical components, and improved cable routing. These measures resulted in slight but meaningful improvements in both manual and automatic DFA indices, while also increasing serviceability and automation readiness.

From an economic perspective, a detailed cost analysis across multiple demand scenarios showed that manual assembly is significantly more cost-effective in the current context. The required investment for a fully automated solution is not justifiable given the moderate production volume, limited product standardization, and the relatively small time savings achievable through automation. Consequently, we recommend manual assembly supported by selective mechanization as the most viable strategy.

Overall, the project demonstrated how structured engineering methods can be used to analyze, optimize, and document a real-world assembly process in detail. Beyond technical results, we gained valuable insight into the trade-offs between flexibility, cost, complexity, and automation potential, skills that will carry over into future product and process development projects.

Appendix

Link to the Excel File with the Liaison Sequence Diagram:

Liason sequence diagram.xlsx

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