# Design Optimization of a Handcycle Manual Wheelchair using the Design for Manufacture and Assembly (DFMA) Approach

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## ABSTRACT

Handcycles offer a good mobility option for people with lower limb disabilities, encouraging them to be more mobile and engaged in the **community**. However, the conventional handcycle designs are often characterized by the high manufacturing costs attributed to the higher number of components of the handcycle and complicated assembling processes. These are limitations that make them less affordable and accessible to people with lower limb disabilities. The purpose of this study is to design a Manual wheelchair handcycle to enhance its manufacturability through the Design for Manufacture and Assembly (DFMA) approach to reduce the manufacturing cost and assembly complexity. The handcycle idea was developed in Solid Works and analysed with the Boothroud-Dewhurst DFMA methodology. The optimization of the design involved reducing the number of parts and simplifying assembly tasks to ensure that the product could be manufactured at a lower cost without sacrificing its functionality. The optimized design reduced the total number of components from 81 to 35, decreased assembly labour time by 72.8%, increased the DFA index from 25.16% to 71.43%, reduced the manufacturing cost from RM1,417.38 to RM206.31, and lowered the product weight from 34.79 kg to 12.79 kg. The results demonstrate that the DFMA approach is an effective method for developing affordable, efficient, and user-friendly handcycle designs. This study provides a practical framework for optimizing the design of assistive mobility devices and supports the development of cost-effective products that enhance accessibility for wheelchair users.

**Keywords:** Handcycle, Manual wheelchair, DFMA (Design for Manufacture and Assembly), Product optimization.

## INTRODUCTION

Manual wheelchairs remain one of the most widely used assistive mobility devices for individuals with lower-limb disabilities. Manual wheelchairs can provide an effective way for independent mobility but propulsion using upper-limb movement may result in shoulder pain and muscle fatigue which reducing user comfortability [1], [2]. Recent biomechanical evidence shows that repetitive propulsion and shoulder loading contributed to musculoskeletal disorders among long-term wheelchair users. This indicates the need for mobility solution that can minimize upper-limb strain while maintaining functional independence [3]. Handcycle have become a viable alternative to conventional manual wheelchairs by improving propulsion efficiency, reducing shoulder loading, and promoting greater user independence. Handcycle is different compared to hand-rim propulsion as it using hand-crank mechanism that provides power transfer and improved mechanical efficiency during propulsion [4]. Depending on user requirements, handcycle are designed for handcycles are designed for rehabilitation, daily transportation or competitive sports. As for daily use model, it mainly emphasizes on comfort, accessibility and ease of operation. Furthermore, regular handcycling has been associated with improved cardiovascular fitness, upper-body strength and social participation which makes it an effective mobility solution for long-term wheelchair users [4], [5].

In Malaysia, the demand for assistive mobility devices continues to increase with the growing population of persons with disabilities. According to the Department of Statistics Malaysia (DOSM), 805,509 persons with disabilities were registered in 2024 with physical disabilities representing one of the largest disability categories [6]. Despite the functional advantages of handcycles, their widespread adoption remains limited because commercially available products are generally characterized by high manufacturing costs, excessive component counts, relatively heavy structures and complex assembly processes [7]. These factors contributed to high production and maintenance cost that reduce affordability and accessibility especially for users in developing countries.

Design for Manufacture and Assembly (DFMA) is now an accepted engineering process for making products manufacturable by incorporating manufacturing and assembly related factors into the design process from an early stage in the development of the product [8]. The main goal of DFMA is to reduce the number of components, ease assembly processes and to standardize components and optimize manufacturing processes. It helps to reduce production costs, increase product quality, reliability and maintainability [9]. For example, Prasad et al. [10] used the Boothroyd–Dewhurst DFMA methodology to redesign a hair clipper with a reduction in the number of components and the complexity of assembly operations. The redesigned product showed a significant improvement in assembly time from 322.91s to 163.81s and the DFA efficiency from 7.43% to 14.65%, it was seen how effective DFMA was in enhancing the efficiency of product assembly. The same, Lee and Nawawi [11] employed the Boothroyd–Dewhurst DFA method for the optimization of the design and assembly of a drill grinder machine. The main objectives of the redesign were to reduce part count, simplify assembly and improve manufacturing costs, leading to greater design efficiency and fewer assemblies. DFMA has been used successfully in a wide variety of engineering disciplines, such as automotive, aerospace, consumer products and industrial equipment, and improvements in the efficiency of manufacturing and assembly have been reported.

However, although extensive research has been conducted on handcycle biomechanics and rehabilitation performance but relatively few studies have investigated the optimization of handcycle design from a manufacturing perspective. The focus of current literature is on propulsion biomechanics, ergonomic performance and rehabilitation results, while the systematic application of product design methods like DFMA in reduction of component numbers, facilitation of assembly and reduced manufacturing cost is far less studied [4, 5]. Furthermore, existing commercial handcycle are still relatively high production costs due to complex product design and manufacturing requirements. This imposed restriction underlines the need for a systematic framework for product design optimization, taking into account product functionality, manufacturability, assembly efficiency and production cost.

Therefore, this research is designed to optimize the design of manual wheelchair handcycle using DFMA approach. A conceptual handcycle model was developed in Solid Works CAD and subsequently evaluated using the Boothroyd Dewhurst DFMA approach. This method seeks to minimize the number of parts, to streamline assembly tasks, to enhance manufacturability and cost effectiveness, and to ensure adequate structural strength and functionality. The findings of this study are expected to provide a practical design framework for the development of affordable, manufacturable and user-oriented assistive mobility devices that improve accessibility and support sustainable product development

## METHODOLOGY

This study implemented the DFMA approach to optimize the design of a manual wheelchair handcycle. DFMA is a systematic product development methodology that integrates manufacturing and assembly considerations during the early stages of product design to improve manufacturability, simplify assembly operations, reduce product complexity and minimize production costs while maintaining product functionality and quality [8]. The methodology enables designers to reduce unnecessary components, standardize product architecture, and improve manufacturing and assembly efficiency through systematic design evaluation and iterative optimization [9], [12]. The research methodology comprised five sequential stages: (i) Product Design Specification (PDS), (ii) conceptual design development, (iii) computer-aided design (CAD) modelling, (iv) DFMA evaluation, and (v) design optimization, as illustrated in Figure 1.

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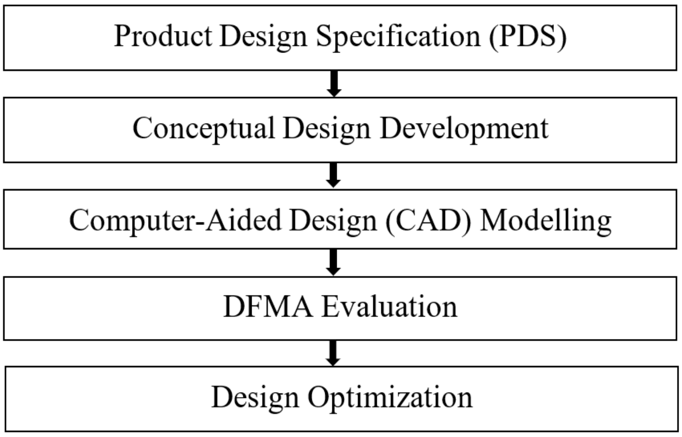


Figure 1: Research methodology

Initially, the Product Design Specification (PDS) was established according to Pugh's total design methodology [14] to define the functional requirements, engineering specifications, user needs, manufacturing constraints, and performance objectives of the proposed design. The finalized PDS was established based on the identified customer requirements and the functional requirements of the Handcycle Manual Wheelchair. The PDS served as the primary design guideline throughout the product development process to ensure that the optimized design satisfied the intended functional, ergonomic and manufacturing requirements as depicted in Table 1.

Table 1: PDS of Handcycle Manual Wheelchair

| **PDS** | **Requirement** |
|---|---|
| Load Capacity | At least 130 kg |
| Control Configuration | Interchangeable between left and right sides |
| Compatibility | Compatible with the intended wheelchair configuration |
| Attachment System | Secure, detachable, and easy to operate |
| Safety | Stable and secure during normal operation |
| Braking System | Reliable and easily accessible to the user |
| Ergonomics | Comfortable and suitable for different user capabilities |
| Material | Sufficient strength with consideration of weight and manufacturability |
| Assembly | Simple with minimum assembly complexity |
| **Maintenance** | Major components should be accessible for inspection and maintenance |
| **Portability** | Easy to detach, handle, and store |
| **Durability** | Able to withstand repeated normal usage without structural failure |

Subsequently, a conceptual handcycle model was developed using SolidWorks CAD software. Three-dimensional component models, assembly models, and engineering drawings were created for the design visualization and product verification. A complete Bill of Materials (BOM) was then drawn up to identify all components required for manufacturing and assembly before conducting the DFMA evaluation [13]. The current and new design were analysed using the Boothroyd–Dewhurst DFMA approach. The DFA analysis was used to evaluate component handling, insertion, orientation, accessibility and fastening requirements to estimate assembly time and overall design efficiency. The DFM analysis was performed to evaluate manufacturability of the product by analysing material selection, component geometry, manufacturing processes and process capability to identify opportunities for improving manufacturability and reducing production costs [8], [9].

The handcycle design was iteratively improved based on the outcomes of the DFMA evaluation which included the elimination of unnecessary parts, integration of compatible parts, simplification of assembly process and selection of suitable manufacturing technique and material. The optimized design was then compared with the initial design using the following performance indicators of DFMA which include number of parts, estimated assembly time, manufacturing cost and design efficiency to assess the effectiveness of the proposed design optimization approach [8].

# RESULTS AND DISCUSSION

## Current Handcycle of Handcycle for Manual Wheelchair

Figure 2 shows that the current handcycle consists of several fastening components distributed across multiple subassemblies. The extensive use of threaded fasteners makes products more complex because extra handling, positioning, and tightening steps are needed during assembly. Hence the assembly is more time-consuming and labour intensive, and there is a need to use DFMA for optimizing the product structure to make the assembly more efficient.

Figure 2: Assembly Drawing of the current Design Handcycle

The current design handcycle assembly tree is shown in Figure 3. There are 5 subassemblies for the product consist of handlebar subassembly, box subassembly, wheel subassembly, brake caliper subassembly and clamp subassembly.

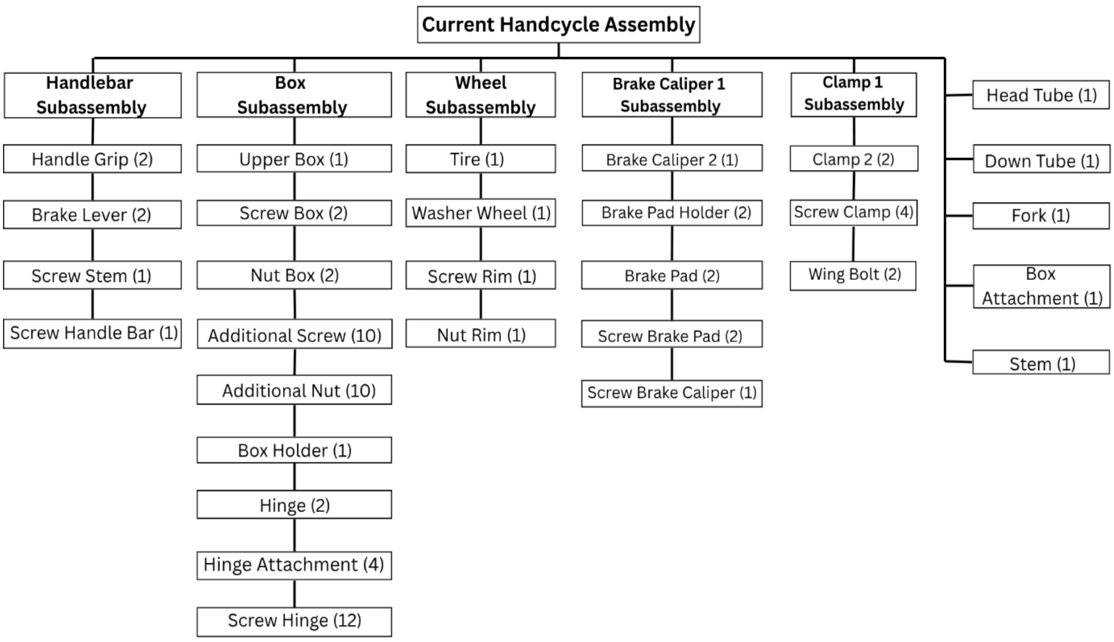


Figure 3: Assembly Tree of the Current Design Handcycle Assembly

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Figure 4 shows an exploded assembly drawing of the current handcycle design.. The exploded view shows the spatial relationships of the individual components - each component is designated with an appropriate balloon number, which corresponds to the appropriate Bill of Materials (BOM). This representation also gives a comprehensive view of the product configuration and assembly steps and allows potential assembly problems to be identified before manufacture and unnecessary parts to be identified. The exploded view also helps with Design for Assembly (DFA) analysis since it provides a clear view of the accessibility, handling and fastening needs and assembly sequence of the components.

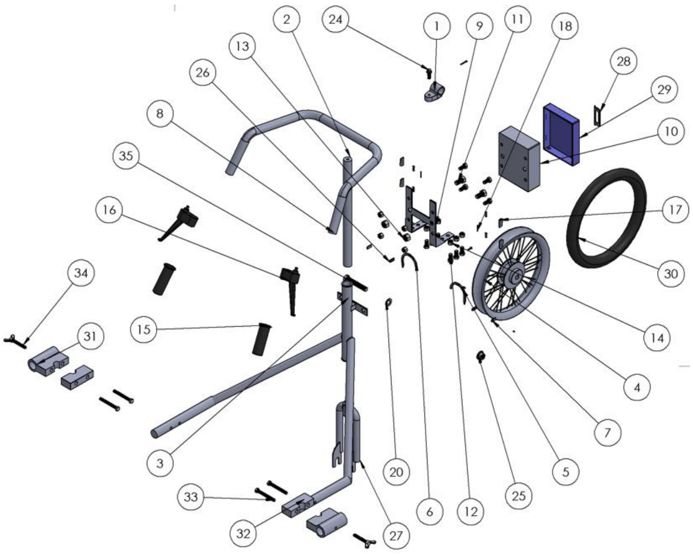


Figure 4: Exploded View of the Current Handcycle Design with BOM

Table 2 lists the full BOM for the current handcycle design. The design has 35 different part types and 81 individual parts which are required to be assembled to create the whole product. The handcycle is made up of the primary structural components, stem, head tube, down tube, fork and wheel assembly, and functional components, handlebar, brake system, storage box, clamps, hinges and 5 and fastening elements. A significant percentage of the total number of components are standard fasteners, such as screws, nuts, washers and clamps. The wide use of fastening parts makes the assembly more complicated and longer, adds to inventory and manufacturing costs.

Thus, there are significant opportunities to improve the existing product structure based on DFMA methodology. Based on the above, the design optimization proposed is to minimize the complexity of the assembly process, standardize components, remove unnecessary parts and improve the manufacturability and the manufacturing cost of the handcycle without reducing the required functional performance of the handcycle. In summary, the assembly model, the assembly tree, the exploded view, and the BOM is the minimal information necessary for the following DFMA analysis. These representations allow for systematic assessment of product architecture, manufacturability, and assembly efficiency, and help identify potential design changes that can simplify assembly, boost manufacturability, and drive down manufacturing costs.

Table 2: BOM of the current Handcycle Design

| No. | Part Name | Material | Process | Quantity |
|---|---|---|---|---|
| 1. | Stem | Generic Stainless Steel | Cut and Machining Process | 1 |
| 2. | Head Tube | Generic Stainless Steel | Cut and Machining Process | 1 |
| 3. | Down Tube | Generic Stainless Steel | Cut and Machining Process | 1 |
| 4. | Wheel | Generic Stainless Steel | Cut and Machining Process | 1 |
| 5. | Brake Calliper 1 | Generic Stainless Steel | Cut and Machining Process | 1 |
| 6. | Brake Calliper 2 | Generic Stainless Steel | Cut and Machining Process | 1 |
| 7. | Brake Pad Holder | Generic Stainless Steel | Cut and Machining Process | 2 |
| 8. | Handlebar | Generic Stainless Steel | Cut and Machining Process | 1 |

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| | | | | |
|---|---|---|---|---|
| 9. | Box Attachment | Generic Stainless Steel | Cut and Machining Process | 1 |
| 10. | Lower Box | PVC | Injection Molding | 1 |
| 11. | Screw (Box) | Stainless Steel | Cut and Machining Process | 2 |
| 12. | Additional Screw (Box) | Stainless Steel | Cut and Machining Process | 10 |
| 13. | Nut (Box) | Stainless Steel | Cut and Machining Process | 2 |
| 14. | Additional Nut (Box) | Stainless Steel | Cut and Machining Process | 10 |
| 15. | Handle Grip | Nylon 6/6 Polyamide | Injection Molding | 2 |
| 16. | Brake Lever | PVC | Injection Molding | 2 |
| 17. | Hinge | PVC | Injection Molding | 4 |
| 18. | Hinge Attachment (Box) | PVC | Injection Molding | 2 |
| 19. | Screw (Hinge) | Stainless Steel | Cut and Machining Process | 12 |
| 20. | Washer | Stainless Steel | Cut and Machining Process | 1 |
| 21. | Screw (Handlebar) | Stainless Steel | Cut and Machining Process | 1 |
| 22. | Screw (Brake Pad) | Stainless Steel | Cut and Machining Process | 2 |
| 23. | Screw (Brake Calliper) | Stainless Steel | Cut and Machining Process | 1 |
| 24. | Screw (Stem) | Stainless Steel | Cut and Machining Process | 1 |
| 25. | Nut (Rim) | Stainless Steel | Cut and Machining Process | 1 |
| 26. | Brake Pad | Polyester (PBT) | Cut and Machining Process | 2 |
| 27. | Fork | Generic Stainless Steel | Cut and Machining Process | 1 |
| 28. | Box Holder | PVC | Injection Molding | 1 |
| 29. | Upper Box | PVC | Injection Molding | 1 |
| 30. | Tyre | Nylon 6/6 Polyamide | Injection Molding | 1 |
| 31. | Clamp Part 1 | Low Carbon Alloy Steel | Cut and Machining Process | 2 |
| 32. | Clamp Part 2 | Low Carbon Alloy Steel | Cut and Machining Process | 2 |
| 33. | Screw (Clamp) | Stainless Steel | Cut and Machining Process | 4 |
| 34. | Wing Bolt (Clamp) | Stainless Steel | Cut and Machining Process | 2 |
| 35. | Screw (Rim) | Stainless Steel | Cut and Machining Process | 1 |
| Total: | | | | 81 |

**DFA Result of Current Design**

In the present handcycle design, the DFA analysis was carried out using the Boothroyd–Dewhurst DFA software in order to assess the assembly efficiency of the product. A total of 81 entries were identified, of which 22 parts were identified as essential parts and 4 parts as candidates for elimination, offering opportunities to simplify the design by eliminating or combining parts as detailed in Table 3.

Table 3: Data entries including repeats for Current Design

| **Entries including repeats** | **Current Design** |
|---|---|
| Parts meet minimum part criteria | 22 |
| Parts are candidates for elimination | 4 |
| Analysed subassemblies | 6 |
| Separate assembly operations | 49 |
| Total entries | 81 |

Table 4 shows the distribution of handcycle assembly labour time for the existing handcycle design. The labour time for each entry is calculated by multiplying the assembly time of each component type with the defined labour rate. The total assembly labour time of the product is 1063.04 seconds. Of that total, 235.06 seconds are assigned to parts that have been reduced to the minimum part size, 32.08 seconds are allocated to parts that are identified as candidates for elimination, 69.94 seconds are allocated to the insertion of analyzed subassemblies and 725.96 seconds are allocated to the separate assembly operations. The assembly time of candidates for elimination is the time taken to assemble nonfunctional or unnecessary parts such as fasteners, which are not directly related to the essential functions of the product. The Design for Assembly (DFA) Index (Design Efficiency) is the ratio of the product's efficiency to an optimum product [8].

It is calculated using the following equation:

DFA Index (%) = ($T_{ideal}$) / ($T_{total}$) x 100%

$T_{ideal}$ is the theoretical minimum assembly time required for essential components (267.46 seconds) and $T_{total}$ is the assembly labour time (1063.04 seconds).

DFA Index (%) = (267.46 s) / (1063.04 s) x 100% = 25.16%

The significantly high time associated with separate assembly operations reflects opportunities to simplify handling and joining processes, which could improve the DFA Index of 25.16% by reducing unnecessary operations and part counts as depicted in Figure 5.

Table 4: Data assembly labour time for Current Design

| Assembly Labour Time (seconds) | Current Design |
|---|---|
| Parts meet minimum part criteria | 235.06 s |
| Parts are candidates for elimination | 32.08 s |
| Insertion of analysed subassemblies | 69.94 s |
| Separate assembly operations | 725.96 s |
| Total Assembly Labour Time | 1063.04 s |
| DFA Index (Design efficiency) | 25.16 % |

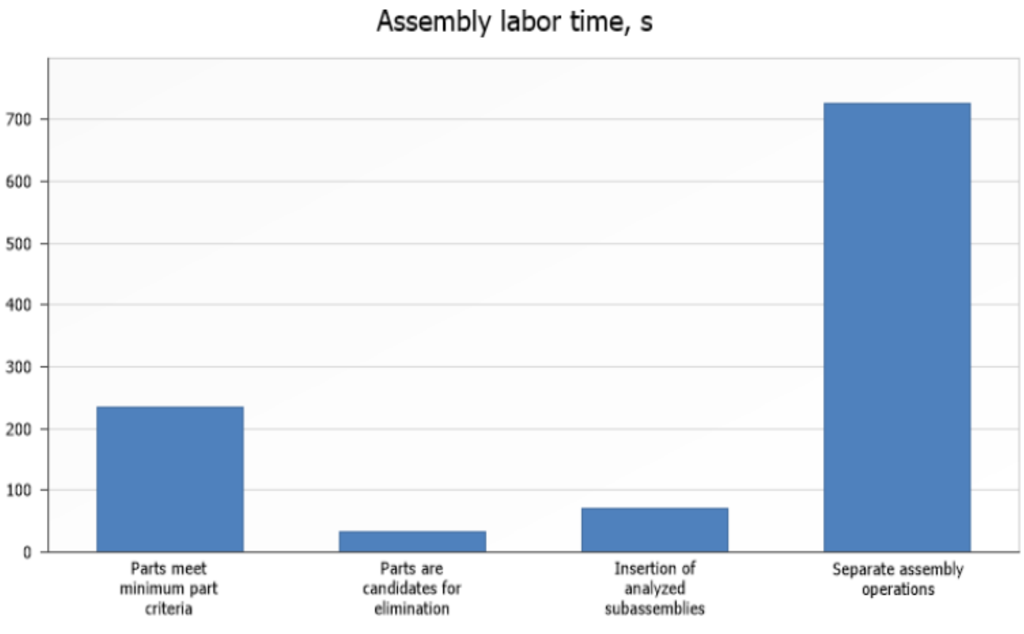


Figure 5: Breakdown of assembly time per product for Current Design

**DFM Result of Current Design**

The cost assessment of handcycle production was performed using the DFM Concurrent Costing software to evaluate both the unit manufacturing cost and the overall tooling investment. For each handcycle, the assembly process contributes RM66.88 to the unit cost, while the manufacturing cost of individual parts accounts for RM1,350.26, representing the largest proportion of the total unit cost, as shown in Figure 6. The total manufacturing cost, excluding tooling, is therefore RM1,417.14 per unit. An additional tooling cost of RM0.24 per unit is incurred, resulting in a total unit manufacturing cost of RM1,417.38, as shown in Table 5.

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Table 5: DFMA analysis for current design handcycle

| **Product Data** | **Result** |
|---|---|
| **Per Product Costs** | |
| Assembly process | RM 66.88 |
| Manufacturing piece part | RM 1,350.26 |
| Total cost without tooling | RM 1,417.14 |
| Addition tooling cost | RM 0.24 |
| Total cost per product | RM 1,417.38 |
| | |
| **Total Tooling Investment** | |
| Assembly tools and fixtures | RM 0 |
| Manufacturing tooling | RM 2,166.70 |
| Total investment | RM 2,166.70 |
| | |
| **Production Life Data and Weight** | |
| Life volume | 10,000 units |
| Total production life cost | RM 14,174,707 |
| Total weight | 34.79 kg |

In terms of tooling investment, only manufacturing tooling is required, amounting to RM2,166.70, with no additional costs allocated to assembly tooling or fixtures, as shown in Table 5. This indicates that the assembly process does not demand special equipment, thus reducing the assembly setup time and the necessity for custom jigs and fixtures. The first investment in tooling is required to develop or buy precision manufacturing tools to maintain consistency, dimensional accuracy and quality throughout the manufacturing process. The cost analysis was based on an assumed volume of production for the lifecycle of 10,000 units, which gives a total lifecycle production cost of RM14,174,707. Apart from production cost, product weight is another important design parameter which is currently 34.79 kg for the handcycle. The relatively high weight can have implications for material usage, logistics, handling and end user usage. If these factors are considered along with the Design for Assembly (DFA) metrics, opportunities can be identified to optimize the number of parts and materials, potentially resulting in lower manufacturing and assembly costs, reduced weight, and greater productivity throughout the life of the product.

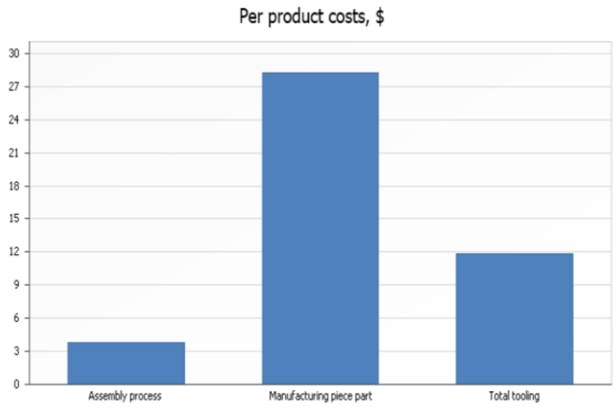


Figure 6: Cost Breakdown for Current Design Handcycle (DFM costingsofware)

**Propose a New Design**

Table 6 shows the total number of components that were identified for elimination, integration or redesign resulting an estimated assembly time savings of 613.82s. These are typically threaded components such as screws, nuts and wing bolts which must be repeatedly handled and tightened in assembly. Table 7 shows the another 36.01s are saved when the 12 components are identified as having difficulties in handling and inserting. The awkward orientation, alignment and accessibility of components like the downtube, clamps, stem and hinge require extra assembly work. Overall, the DFA results indicate that reducing unnecessary fastening elements, integrating compatible components and improving component handling can significantly simplify the assembly process, improve manufacturability and reduce production costs while maintaining the functional performance of the handcycle. These findings provide the basis for the subsequent development of the optimized handcycle design.

Table 6: Suggested parts for reducing the number of items

| Part Name | Parent Assembly | Part Quantity | Time Saving (s) |
|---|---|---|---|
| Additional Nut (Threaded fastening) | Box | 10 | 190.52 |
| Additional Screw (Snap/Push Fitting) | Box | 10 | 105.74 |
| Screw Hinge (Threaded Fastening) | Box | 12 | 59.52 |
| Screw Stem (Thread Tightening) | Handlebar | 1 | 29.02 |
| Screw Handlebar (Thread Tightening) | Handlebar | 1 | 29.02 |
| Screw Brake Pad (Thread Tightening) | Brake Calliper | 2 | 47.32 |
| Screw Clamp (Thread Tightening) | Clamp | 4 | 94.64 |
| Wing Bolt (Thread Tightening) | Clamp | 2 | 58.04 |
| Total: | | 42 | 613.82 |

Table 7: Suggested parts for reducing difficulties with handling and inserting

| Part Name | Parent Assembly | Handling or insertion difficulties | Part Quantity | Time Saving (s) |
|---|---|---|---|---|
| Down tube | Current Handcycle | Two persons, Awkward | 1 | 13.63 |
| Clamp 1 | Current Handcycle | Nest or tangle, Careful handling, Alignment | 2 | 4.27 |
| Clamp 2 | Clamp 1 | Nest or tangle, Careful handling | 2 | 4.00 |
| Stem | Current Handcycle | Severe nest or tangle, Careful handling, Alignment | 1 | 3.00 |
| Handlebar | Current Handcycle | Alignment | 1 | 2.30 |
| Box Attachment | Current Handcycle | Careful handling | 1 | 2.00 |
| Hinge | Box | Slippery, Careful handling, Alignment | 4 | 6.81 |
| Total: | | | 12 | 36.01 |

**New Design of Handcycle for Manual Wheelchair**

A new handcycle design was developed by incorporating the design improvements identified through the Boothroyd–Dewhurst DFMA analysis. The primary objective of the redesign was to minimize the number of

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components in the product architecture, by removing components that were not necessary, adding components that were compatible and reducing the number of fastening operations without compromising the design requirements. The new design maintains the basic features of the concept and has a more compact and simplified assembly configuration as illustrated in Figure 7.

Figure 7: Assembly Drawing of the New Design

The assembly structure of the optimized handcycle is presented in Figure 8 and exploded view of handcycle assembly is presented in Figure 9. The optimized assembly is less cumbersome than the current design, has fewer sub-components, and has fewer relationships between them during assembly. The exploded view further shows that multiple redundant components and components fasteners have been removed or combined to enhance access of the components and minimize possible handling and insertion issues during assembly. These design enhancements are expected to make the assembly process easier, decrease assembly time and improve manufacturability.

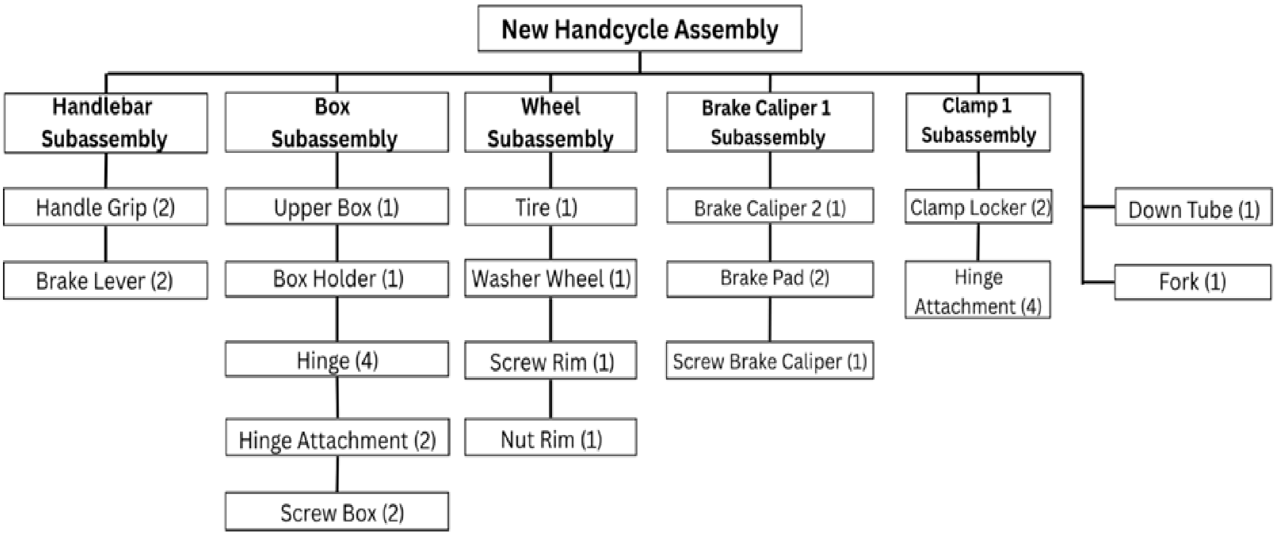


Figure 8: Assembly Tree of the New Design Handcycle Assembly

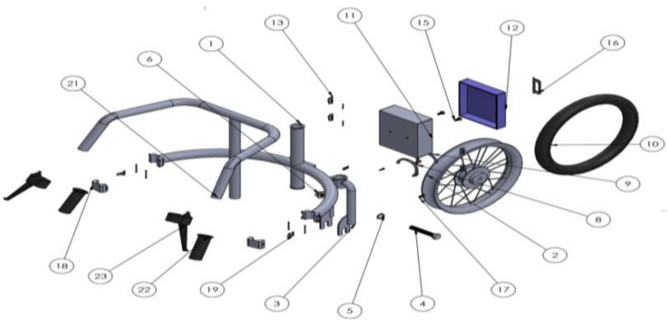

Figure 9: Exploded View of the New Design Handcycle

The new handcycle consists of 23 unique components and 35 individual parts, compared with 35 unique components and 81 individual parts in the current design, as presented in Table 8. This results in 46 individual parts being replaced (56.8%) by way of component integration and stripping out of superfluous fastening components. This significant decrease in part count should also help reduce manufacturing and inventory expenses, assembly process, and production efficiency. Overall, the redesign illustrates the success of the DFMA methodology to create a more manufacturable, cost-effective and assembly efficient assistive mobility device that meets the design goals.

Table 8: BOM of the New Design Handcycle

| No. | Part Name | Material | Process | Quantity |
|---|---|---|---|---|
| 1. | Down Tube | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 2. | Wheel | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 3. | Fork | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 4. | Screw Rim | Stainless Steel | Cut and Machining Process | 1 |
| 5. | Washer Rim | Stainless Steel | Cut and Machining Process | 1 |
| 6. | Nut Rim | Stainless Steel | Cut and Machining Process | 1 |
| 7. | Screw Brake Calliper | Stainless Steel | Cut and Machining Process | 1 |
| 8. | Brake Calliper 1 | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 9. | Brake Calliper 2 | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 10. | Tyre | Nylon 6/6 Polyamide | Injection Molding | 1 |
| 11. | Lower Box | PVC | Injection Molding | 1 |
| 12. | Upper Box | PVC | Injection Molding | 1 |
| 13. | Hinge | PVC | Injection Molding | 4 |
| 14. | Hinge Attachment (Box) | PVC | Injection Molding | 2 |
| 15. | Screw Box | Stainless Steel | Cut and Machining Process | 2 |
| 16. | Box Holder | PVC | Injection Molding | 1 |
| 17. | Brake Pad | Polyester (PBT) | Injection Molding | 2 |
| 18. | Clamp | Generic Low Carbon Steel | Cut and Machining Process | 2 |
| 19. | Clamp Locker | Generic Low Carbon Steel | Cut and Machining Process | 2 |
| 20. | Hinge Attachment | Generic Low Carbon Steel | Cut and Machining Process | 4 |
| 21. | Handlebar | Generic Low Carbon Steel | Cut and Machining Process | 1 |
| 22. | Hand Grip | Nylon 6/6 Polyamide | Cut and Machining Process | 2 |
| 23. | Brake Lever | PVC | Injection Molding | 2 |
| Total: | | | | 35 |

**DFA Result of the New Design**

The assembly analysis of the new handcycle was conducted using the Boothroyd–Dewhurst DFA software to evaluate design efficiency and identify opportunities for assembly optimization. The final design consists of 35 entries, including 17 essential parts that satisfy the minimum part criteria and eight parts identified as candidates for elimination. These improvements significantly reduce assembly complexity and demonstrate the effectiveness of the redesign in simplifying the product architecture, as presented in Table 9.

Table 9: Data entries including repeats for New Design

| Entries including repeats | New Design |
|---|---|
| Parts meet minimum part criteria | 17 |
| Parts are candidates for elimination | 8 |
| Analysed subassemblies | 5 |
| Separate assembly operations | 5 |
| Total entries | 35 |

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The distribution of labour time required for assembling the new design is given in Table 10. Overall assembly time has been cut to 289.06 seconds which 146.54 seconds are essential parts, 45.99 seconds are parts recommended to be eliminated, 59.51 seconds are subassembly insertions and 37.02 seconds are separate assembly operations. This is seen as better handling and integration as the demand for man-hours in nonfunctional items has been reduced and the time for independent operations has been minimized. Design for Assembly (DFA) Index (Design Efficiency) is calculated using the Boothroyd Dewhurst formula:

DFA Index (%) = (Tideal) / (Ttotal) x 100%

Tideal is the theoretical minimum assembly time required for essential components (206.48 seconds) and Ttotal is the assembly labour time (289.06 seconds).

DFA Index (%) = (206.48 s) / (289.06 s) x 100% = 71.43%

These changes have resulted in a significantly higher DFA Index at 71.43 which emphasize the improved efficiency of the assembly and possible lower manufacturing costs as indicated in Figure 10.

Table 10: Data assembly labour time for New Design

| Assembly Labour Time (seconds) | Current Design |
| --- | --- |
| Parts meet minimum part criteria | 146.54 s |
| Parts are candidates for elimination | 45.99 s |
| Insertion of analysed subassemblies | 59.51 s |
| Separate assembly operations | 37.02 s |
| Total Assembly Labour Time | 289.06 s |
| DFA Index (Design efficiency) | 71.43 % |

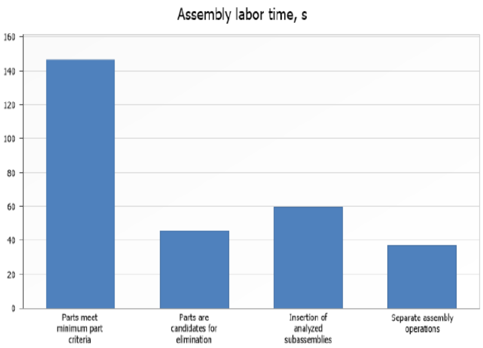


Figure 10: Breakdown of Assembly Time Per Product for New Design

**DFM Result of New Design**

The new handcycle was subjected to a detailed cost analysis using DFM Concurrent Costing software to provide a breakdown of the unit manufacturing cost and total investment requirements. The assembly process contributes RM17.79 to the unit cost, while the manufacturing of individual parts accounts for RM132.73. The total manufacturing cost, excluding the tooling cost per unit, is calculated at RM150.52. Besides, the allocation of tooling cost is RM55.79 per unit that gives RM206.31 manufacturing cost per handcycle. The results of the structured cost evaluation presented in Table 11 illustrate how the selection of the manufacturing processes and part simplification will affect the total cost of the unit.

Table 11: DFMA analysis for New Design Handcycle

| Product Data | Result |
| --- | --- |
| **Per Product Costs** | |
| Assembly process | RM17.79 |
| Manufacturing piece part | RM132.73 |

| | |
|---|---|
| Total cost without tooling | RM150.52 |
| Total tooling cost | RM55.79 |
| Total cost per product | RM206.31 |
| | |
| **Total Tooling Investment** | |
| Assembly tools and fixtures | RM 0 |
| Manufacturing tooling | RM557,661.80 |
| Total investment | RM557,661.80 |
| | |
| **Production Life Data and Weight** | |
| Life volume | 10,000 units |
| Total production life cost | RM2,062,618.50 |
| Total weight | 12.79 kg |

The total investment in the re-designed handcycle is estimated at RM557,661.80 with all the investment being spent on a manufacturing tooling only and no extra investment in assembly tooling or fixtures. This first investment is required to guarantee efficient production that retains the required dimensional accuracy, component consistency and manufacturing quality throughout the production lifecycle. The total lifecycle production cost is estimated at be approximately RM2,062,618.50 based on an assumed production volume of 10,000 units. The new handcycle can be estimated to have a weight of 12.79 kg/unit, which is a significant reduction of 63.2% from the current design.

The reduction was made by combining parts and removing the excess of fasteners and eliminating unnecessary structure identified during DFMA. The lower product weight is likely to mean greater benefits for material use, handling, logistics and end user use. The functional mechanisms and structural elements crucial to the design were preserved and incorporated into the optimized subassemblies to meet the purpose of the design.

In summary, these results have shown that incorporating DFMA principles in a detailed cost modelling process can help to make informed design decisions to optimize product manufacturability, minimize product weight, and meet economic and operational goals, as presented in Figure 11.

For validation of structural performance, operational safety, and usability of the optimized handcycle further structural analysis, prototype testing and user evaluation must be carried out.

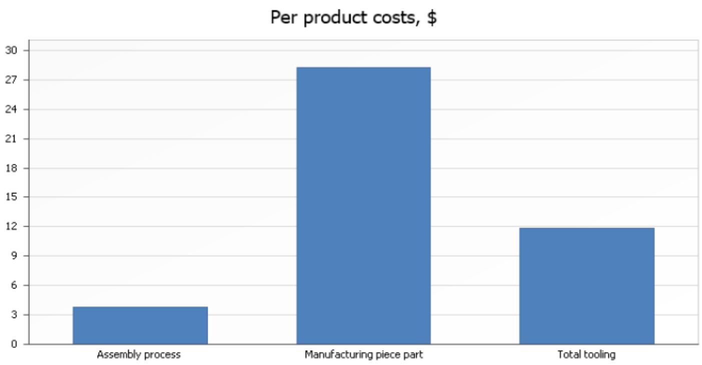


Figure 11: Cost Breakdown for New Design Handcycle (DFM costing software)

## Overall Comparison Between Current Design and New Design

As shown in Table 12, the handcycle that will be used and the new handcycle has been compared and showed great improvement after applying Design for Manufacture and Assembly (DFMA) methodology. DFMA's main goal is to reduce the number of parts and assembly steps to make product architecture easier. The new design has decreased the number of individual components from 81 to 35, which is a reduction of 56.8% in the number of parts. This reduction was achieved by integrating the components and removing any unnecessary fastening components, which led to a simpler product architecture and fewer assembly operations. As a result, the DFA index rose from 25.16% to 71.43%, a 184% relative increase in the efficiency of the assemblies. This significant rise suggests that the new handcycle design is much more efficient to put together than the current design.

This component count reduction also helped significantly with assembly time, manufacturing cost and product weight. The overall assembly labour cost time was decreased from 1,063.04 s to 289.06 s, which is a reduction of 72.8%, mainly because of the reduction of handling, positioning and fastening operations during assembly. Besides, the manufacturing cost per unit was lowered by RM1,417.38 to RM206.31, representing 85.4% reduction in manufacturing cost per unit, and the weight of the product was reduced from 34.79 kg to 12.79 kg, which is a 63.2% reduction in the weight of the product. The weight reduction should lead to less material usage and ease portability and handling for wheelchair users. The current study has some of limitations, however, the findings are largely based on CAD modelling and theoretical DFMA evaluations. Hence, prototype fabrication and experimental testing on handcycles involving structural validation, ergonomic assessment, fatigue assessment, and user assessment is needed in future work to validate the functionality, structural performance, safety, and usability of the new handcycle under real operating conditions.

In summary, the outcomes reported in Table 12 show that DFMA methodology has great potential to improve the manufacturability and assembly efficiency of the handcycle. The new design conforms to the required design specifications with reduction of component count, ease of operation and manufacturing. The results of this study prove that the incorporation of DFMA principles in conceptual design can prove useful for product design optimization and aid in the development of more manufacturable and cost effective assistive mobility devices.

Table 12: Overall comparison between current and new design

| Parameter | Current | New | Improvement |
|---|---|---|---|
| Parts | 81 | 35 | 56.8% |
| Assembly time | 1063.04 | 289.06 | 72.8% |
| DFA index | 25.16 | 71.43 | 184% |
| Cost (RM) | 1417.38 | 206.31 | 85.4% |
| Weight (kg) | 34.79 | 12.79 | 63.2% |

## CONCLUSIONS

The study employed Design for Manufacture and Assembly (DFMA) methodology to optimize the design of a manual wheelchair handcycle. The handcycle has been designed in SolidWorks CAD and analyzed in the Boothrowd-Dewhurst DFMA methodology to determine the potential for part count reduction, assembly simplification and manufacturability. The analysis revealed several improvements that could be made such as redundant fasteners, component handling and insertion issues and complex assembly functions. The findings were the basis for the redesign taking place, through component integration, elimination of unnecessary parts and by simplifying the product architecture. The number of individual parts was decreased from 81 to 35, which is 56.8% reduction. Assembly labour time was reduced from 1,063.04 s to 289.06 s, while the DFA index increased from 25.16% to 71.43%. An estimated manufacturing cost was also lowered from RM1,417.38 per unit to RM206.31 per unit and the product weight was reduced from 34.79 kg to 12.79 kg. The results show significant improvements in assembly productivity, manufacturing costs, and material utilization.

Overall, the findings show that the DFMA methodology can provide a systematic approach to improving the manufacturability and assembly efficiency of assistive mobility devices. The new handcycle has a simpler product architecture, fewer assembly operations, and a lower estimated manufacturing cost than the existing design. The study also highlights the potential of applying DFMA during product development to support the design of more cost-effective assistive mobility products. However, the current findings are based primarily on CAD modelling and theoretical DFMA evaluation. Future work should therefore include prototype fabrication, mechanical and structural testing, ergonomic assessment, fatigue evaluation, and user testing to validate the functionality, safety, durability, and usability of the new handcycle under actual operating conditions.

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