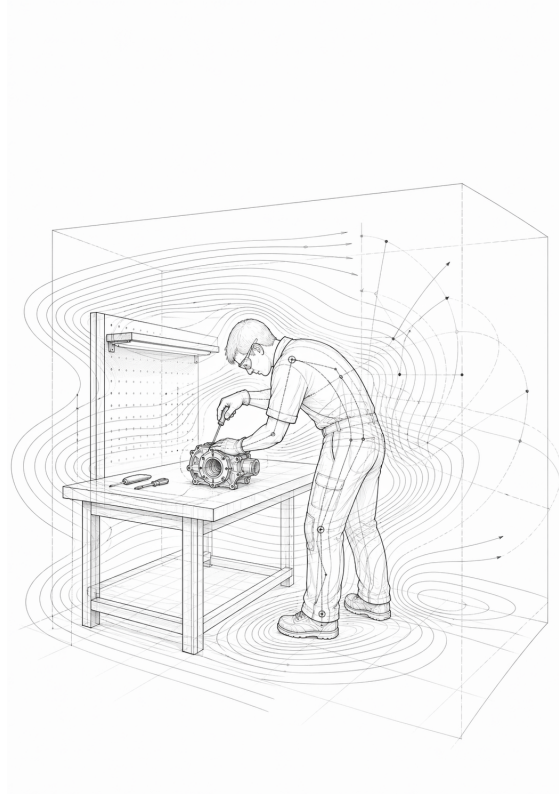




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Evaluation of Ergonomic Risks in Labour-Intensive Remanufacturing Tasks

Master's thesis in Production Engineering

Karthik Vettiyattil Sasikumar
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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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MASTER'S THESIS 2026

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Cover: Image showing a worker in a remanufacturing workstation.

Prompt :Black-and-white technical line drawing of an operator working at a remanufacturing workstation, using a hand tool to disassemble a mechanical component on a workbench. Include ergonomic/Digital Human Modelling visual elements such as posture markers, motion curves, and a transparent 3D analysis box. Minimal academic thesis-cover style, clean white background, fine engineering sketch lines, no text.

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Abstract

Remanufacturing is an important circular economy strategy that prolongs product life and lowers the consumption of virgin raw materials, thereby offering both economic and environmental benefits for companies. However, the process remains labour-intensive because cores arrive in varying states of wear and damage, which creates challenges for operators during their tasks. This study aims to analyse and evaluate the ergonomic risks associated with a labour-intensive remanufacturing workstation by applying ergonomic assessment methods. A mixed-methods approach was adopted, combining theoretical insights from the literature, semi-structured interviews with industry and academic experts, and a simulation-based analysis with ergonomic evaluations using the Rapid Entire Body Assessment (REBA) method and a separate Key Indicator Method (KIM) assessment. Based on the findings from the semi-structured interviews, the disassembly workstation was selected for the simulation-based ergonomics analysis. Three scenarios were modelled and evaluated with REBA in the simulation, while KIM was applied independently to determine the physical workload. The analysis suggests that the disassembly process presents significant ergonomic challenges. Identified risks include awkward body postures, high force exertions, repetitive movements, limited accessibility, and the handling of heavy components. The REBA assessment indicated a moderate ergonomic risk for all three postures studied, whereas the KIM results showed higher physical workload for the bolt removal and trolley transportation tasks. The results indicate that digital simulation combined with ergonomic evaluation tools such as REBA and KIM can effectively identify high-risk activities within remanufacturing workstations.

Keywords: Remanufacturing, Labour-intensive Workstation, Ergonomics, Ergonomic Assessment methods, Manual Disassembly

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Karthik Vettiyattil Sasikumar &
HariKrishna Menon Aravindakshan, Gothenburg, June 2026

Nomenclature

Below is the nomenclature that have been used throughout this thesis.

Units

Symbol	Description
N	Newton, unit of force
m	Meter, unit of length or distance
Nm	Newton meter, unit of torque
kg	Kilogram, unit of mass

Abbreviations

Abbreviation	Description
CE	Circular Economy
DHM	Digital Human Modeling
EAWS	Ergonomic Assessment Worksheet
EEE	Electrical and Electronic Equipment
EOL	End of Life
EOU	End of Use
ERN	European Remanufacturing Network
HDOR	Heavy-Duty and Off-Road Equipment
HF/E	Human Factors and Ergonomics
IMMA	Intelligently Moving Manikin
IRs	Independent Remanufacturers
IT	Information Technology
KIM	Key Indicator Method
LHC	Lifting, Holding, Carrying

MHO	Manual Handling Operation
MRO	Maintenance, Repair and Operation
MSDs	Musculoskeletal Disorders
PP	Pushing, Pulling
OEMs	Original Equipment Manufacturers
QEC	Quick Exposure Check
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
WEEE	Waste Electrical and Electronic Equipment
WMSDs	Work-Related Musculoskeletal Disorders

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1

INTRODUCTION

This chapter contains a brief description of the background of the Master's thesis "Evaluation of Ergonomic Risks in Labour-Intensive Remanufacturing Workstations", in addition to the problem description and purpose. Delimitations and the research questions will conclude the chapter.

1.1 Background

Nowadays, the transition to circular economy(CE) from linear economy (take- make-dispose) has become an excellent strategy to address the sustainability challenges related to the depletion of resources and environmental issues. CE (extend-retain-recover value) it emphasizes reducing the material resource use , keeping the value of products or material in the economy through the strategies such as reuse, repair, recycling and remanufacturing, Among these, remanufacturing is one of the industrial practices that enable the components and products to be restored to new conditions, minimizing the impact on the environment while maintaining the quality and functions[1]. These benefits have positioned remanufacturing as a critical operational strategy for achieving sustainable production within circular economy frameworks, particularly in sectors like automotive, machinery, and heavy equipment manufacturing[2]

The remanufacturing process is considered an environmentally motivated concept (Robert Lund is one of the first researchers who gave remanufacturing advice to potential remanufacturers in the early 1980s). It has been used for quite some time, in industries like the automotive industry, construction equipment, and IT equipment. In the remanufacturing market scenario, activities are commonly carried out by three main types of manufacturers: Original Equipment Manufacturers (OEMs), Independent Remanufacturers (IRs), and Contracted Remanufacturers. This highlights that remanufacturing can be practiced through different organizational arrangements rather than a single industrial model[3].

In the generic remanufacturing process, the following steps are performed: cleaning, inspection, repair, disassembly, testing, storage, and reassembly [4]. For each remanufacturing company, the strategies or the process will be different, e.g. inspection will be the first step, or the product will be disassembled, and error detection will be conducted. Also, the steps in the remanufacturing process could be in a different order, or some steps may be eliminated, depending on the product type, remanu-

facturing volume, etc .Considering economic factors, re-manufactured products are cheaper compared to new product[5]

In terms of economic and environmental benefits, remanufacturing offers better advantages to society, but recent studies have shown that remanufacturing is much more complicated compared to the conventional manufacturing process(because it depends upon the condition of the returned product/core). In remanufacturing environments, the level of automation is lower and remains labour-intensive nature, where worker skill, experience, and decision-making directly influence outcomes [6] [7].

1.2 Aim

The aim of the thesis is to analyse and evaluate the ergonomic risks in remanufacturing processes (In a single workstation or process) using digital simulation.

1.3 Research Questions

- Which work phase, or what work zone, exposes workers to the maximum ergonomic risks/errors, and what ergonomic risks exist in current remanufacturing tasks?
- Which ergonomic assessment can be applied to identify high-risk activities?
- How suitable are digital simulation methods for analyzing ergonomics in remanufacturing operations?

1.4 Objectives

- Draw conclusions from the experts' interviews to evaluate which work process or work zone has the highest ergonomic exposure.
- Develop a digital simulation scenario using expert input, interview findings, and task order at the selected manual remanufacturing workstation.
- Apply ergonomic assessment methods to evaluate the maximum risk elements
- Identify and analyse the ergonomic risks at work zones with higher risk factors
- Propose guidelines for improving ergonomics in the risk-identified workstation

1.5 Scope & Limitation

Included :

- During this thesis, Semi-structured interviews are conducted with industrial and academic experts to get a clear understanding of the remanufacturing process and workstations. The work phases involved are disassembling, cleaning, reconditioning, and assembling. Out of these work phases, we identify the phase with maximum ergonomic risks.

- It is also relevant to acquire some information about the work procedure and working postures, reach requirements, and workstation conditions needed to develop the Digital Human Modeling (DHM) simulation case.
- In this thesis, we opt for the most appropriate ergonomic assessment method within the simulated situation in the identified work phase which could suggest improvement aspects for the specified work operation.

Excluded:

- The analysis is limited to workstation- and task-level ergonomic risk evaluation using established assessment methods.
- The simulation is not intended to capture all real-world variability in remanufacturing activities, including differences in product condition or unforeseen disruptions.
- The research does not assess the entire remanufacturing line; instead, it concentrates on the specific workstation that is modeled in the simulation.
- Development or detailed design for automation solutions, such as cobot systems in the existing process.

2

THEORY

This chapter describes the theoretical background for the remanufacturing process and ergonomics in the manufacturing industry, which are explored throughout the Master's thesis.

2.1 Circular Economy & Remanufacturing

2.1.1 Circular Economy Principle

Circular economy (CE) is defined as a framework that aims to minimize the use of virgin resources, reduce waste generation and close the loop of material and energy through different strategies. From this perspective CE distinguishes between biological cycles and technical cycles as in figure 2.1[8]. Strategies such as reuse, repair, refurbish, recycle, and remanufacturing occur in the technical cycle.

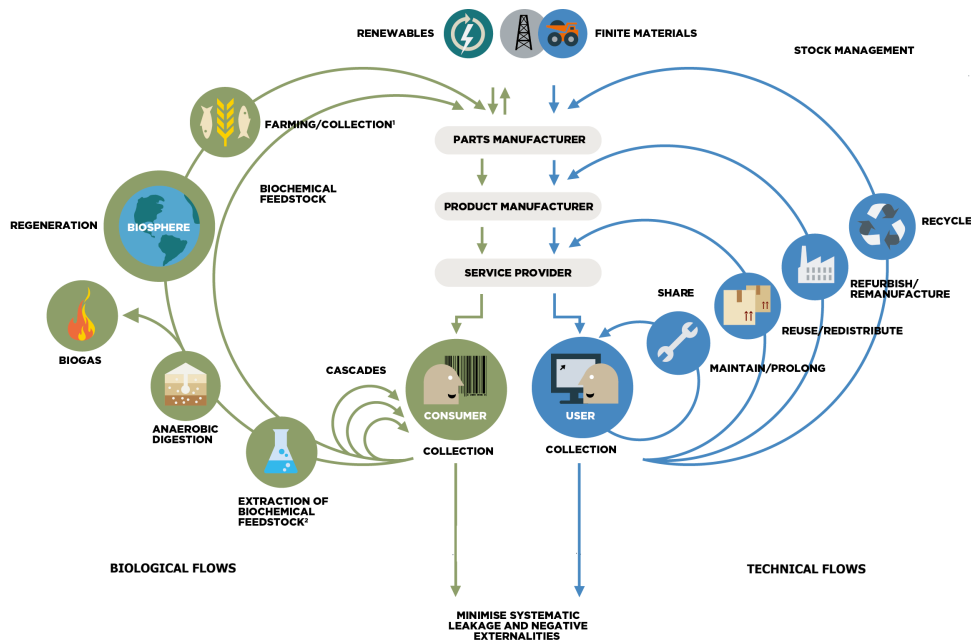


Figure 2.1: Butterfly diagram of the circular Economy. Adapted From [8]

The main goal of the circular economy is to achieve a sustainable society by introducing the extend, retain, and recover value rather than the take–make–dispose where products and materials are maintained within the economy for as long as possible[9].

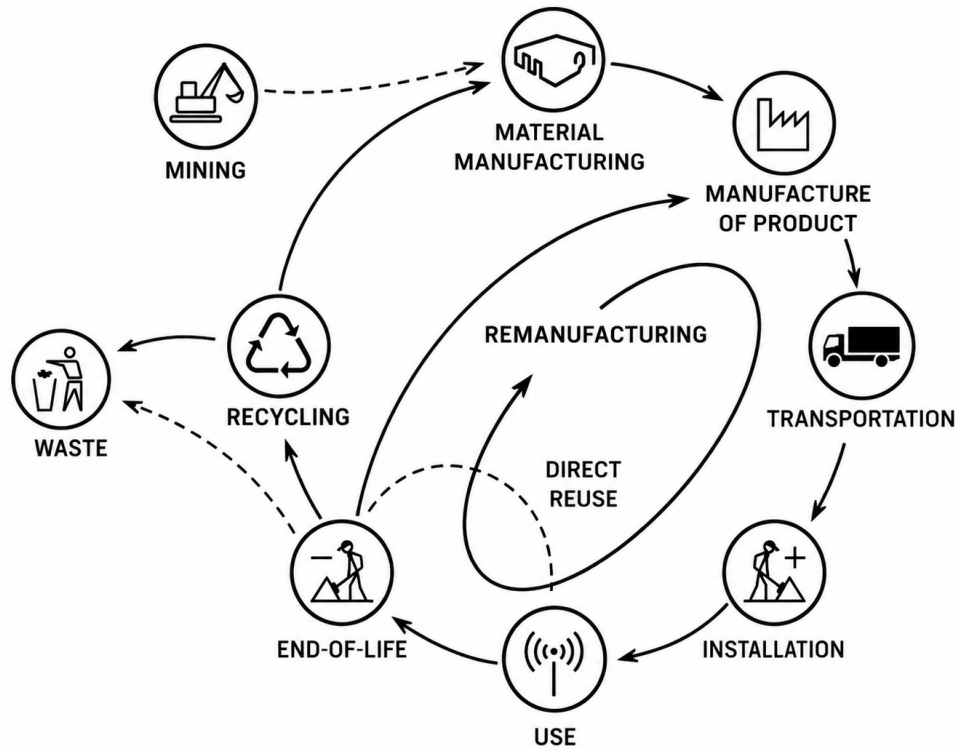


Figure 2.2: Role of remanufacturing within the product life cycle. Adapted from [10]

Figure 2.2 shows how remanufacturing functions within the product life cycle as a closed-loop strategy in CE systems. Through remanufacturing, the functional value of components is preserved by restoring them to a like-new state and returning them to the production cycle. In this way, remanufacturing significantly contributes to feeding materials back into the supply chain without the need for additional raw materials for existing products [11]. Furthermore, a central aim of CE is sustainable development by embedding environmental, economic, and social considerations into production systems.

Social impacts are integrated into production by applying principles of social well-being, safety, and fairness in labor-intensive settings. This is achieved through a systems-oriented approach, which supports improvements not only in how material cycles operate but also in workers’ quality of life, particularly regarding ergonomics in manufacturing and remanufacturing activities. Grounded in social equity and economic development, CE models foster sustainable industrial practices that enhance working conditions and deliver environmental benefits[12].

2.1.2 Overview of Remanufacturing

Remanufacturing is considered a key strategy for the CE, and it is an approach where the end-of-life (EOL) and end-of-use (EOU) products are returned to a condition that is as good as the original version of the product. Its primary purpose is to recover the value of components and materials from used products. And from a societal perspective, remanufacturing can reduce the carbon footprint and material consumption significantly.

From an environmental viewpoint, remanufactured products consume 85% less energy compared to newly manufactured products. As an example, remanufacturing an engine can result in a reduction of 565 kg of CO₂ and 55 kg of steel. It offers economic advantages by providing products at a lower price point—often as low as 60% of the cost of new items[9] while generating revenue from materials that would otherwise be discarded. It also creates social value by employing both non-skilled and highly experienced labour.

While remanufacturing supports environmental, economic, and social benefits, it largely relies on manual labour. This is because returned products/cores typically vary in design, condition, level of wear, and, more generally, exhibit high variability. Such factors make it challenging to implement fully automated remanufacturing processes. In [13], it is shown that, in electronics remanufacturing, human expertise is combined with intelligent technologies, with operators required to handle uncertainties, evaluate product condition, and make flexible decisions throughout the process. Consequently, remanufacturing is considered as a human-centered production activity, in which operator knowledge and ergonomic support are crucial.

2.2 Remanufacturing Process

As Rolf Steinhilper[14] described in the book "Remanufacturing The Ultimate Form of Recycling", one of the landmark publications in the field, remanufacturing is recycling by manufacturing good as new products from used products and restoring the used durable products to a “like new” condition. Steinhilper describes remanufacturing as the highest tier of recycling because it conserves the added value in the original product rather than destroying it through shredding or remelting[15].

Figure 2.3 shows that, compared to other product recovery options (Repair and Reconditioning), remanufacturing upgrades the product the most in terms of quality, warranty and work content. In remanufacturing, the product is totally dismantled and components are restored or replaced; that’s the reason for good quality compared to other options, but it also involves more work compared with conventional manufacturing[3].

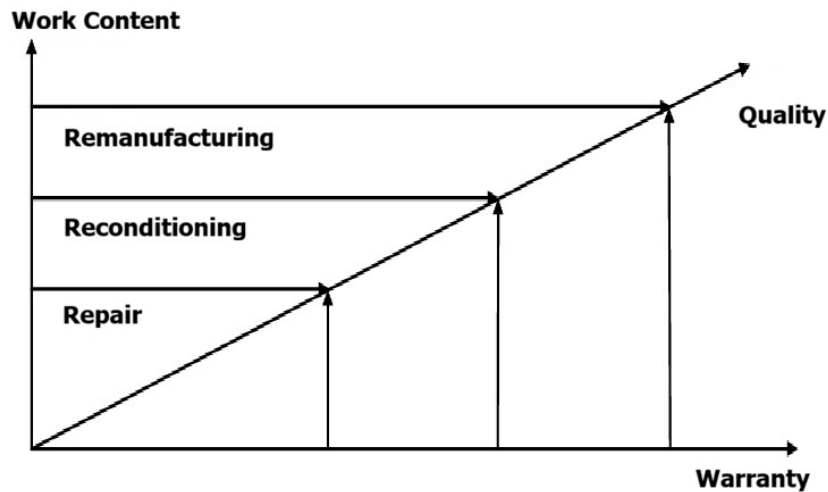


Figure 2.3: Comparison of restoration levels across repair, reconditioning, and remanufacturing processes - Illustration by Karthik Vettiyattil Sasikumar, based on [3]

Remanufacturing spread across industrial sectors such as automotive components, construction equipment, aircraft engines, photocopiers, furniture, industrial bearings [4]. Due to the variety of the product types stages of the remanufacturing, levels of manual intervention also varies across it compare with the conventional manufacturing [14].

2.2.1 Typical Stages Of Remanufacturing

The Remanufacturing process consists of a sequence of stages designed to restore end-of-life products to a new condition comparable to newly manufactured products. Figure 2.4 shows operation stages in remanufacturing .The stages generally include: Inspection , Cleaning , Disassembly , Reprocess , Reassembly , Final testing, Packing [4] [16]. As also mentioned in the background, the order of operation stages will depend on the product and industry.

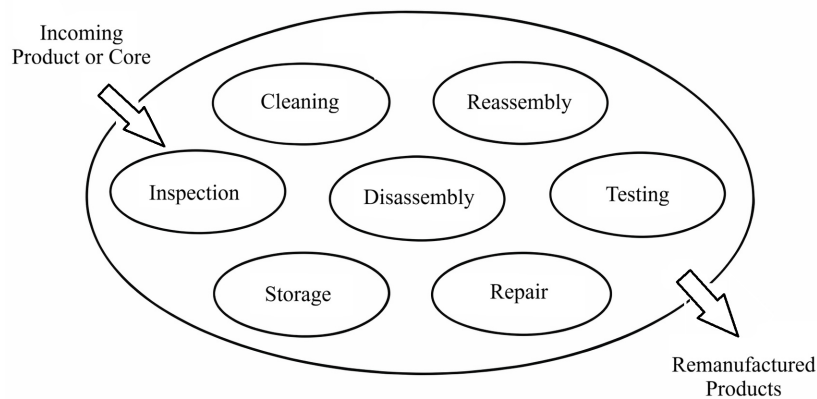


Figure 2.4: Stages in Remanufacturing wich may vary in order. Illustration by Karthik Vettiyattil Sasikumar, based on [16, 4]

- **Collection & Material Handling:** The whole remanufacturing process begins with the collection of the used products, referred to as cores. These collections can be from customers or through reverse logistics services. These returned products are transported to the remanufacturing facility by OEMs, IRs, or contracted remanufacturers, and then sorted and prepared for further processing [17].
- **Inspection:** In this step, remanufacturers will identify whether the returned core is suitable for remanufacturing and type of defect or failure present in the product/core. Sometimes, the core comes with a failure report that indicates the reason. An early critical inspection is important, to avoid unnecessary work on the core [4].
- **Disassembly:** In this stage, the core is dismantled into parts, modules, and components, separating and distinguishing reusable parts from damaged ones, and preparing the core for the upcoming stages of cleaning and further restoration. The time and labour intensity of the stage depend on the product design, joining methods, and condition of the component[18].
- **Cleaning:** Essential stage in the remanufacturing because it removes the dirt, oil, or other types of residues from the product, accumulated during the product's usage life cycle. This improves the visibility of the component surface and the assessment of the condition of the product. The selection of the cleaning method depends on material type, product geometry, and contamination level, and also involves mechanical and chemical cleaning techniques depending on the industrial application[4].
- **Reprocessing:** In the reprocessing stage, the product or parts are restored to their needed functionality, which involves repairing, machining, or changing the worn parts to meet the required specifications. The purpose of this stage is to recover the value of the product while ensuring technical and quality performance.
- **Reassembly:** After the reprocessing is complete, the next step is to reassemble the components into the final product. Reassembly in remanufacturing resembles traditional manufacturing assembly, but it must account for the variability and specific conditions of the recovered parts. As a result, reassembly operations in remanufacturing settings are generally more flexible and more knowledge-intensive than in conventional production. Consequently, they demand substantial technical expertise to ensure that the finished product satisfies its original performance requirements.
- **Final quality test:** As the last stage of the process, the product undergoes testing to verify that it complies with all technical, functional, and quality requirements. At this point, it is confirmed that the remanufactured product achieves the same performance level as the original product and is provided with an equivalent warranty to that of new products (subject to the company's policy)[10].

2.2.2 Remanufacturing Across Different Industries

Remanufacturing is a well-established industrial activity for extending the product life-cycle used in a wide range of sectors, as outlined in the previous sections.

Sector	Turnover (€bn)	Firms	Employment ('000)	Core ² ('000)
Aerospace	12.4	1000	71	5,160
Automotive	7.4	2363	43	27,286
EEE	3.1	2502	28	87,925
Furniture	0.3	147	4	2,173
HDOR	4.1	581	31	7,390
Machinery	1.0	513	6	1,010
Marine	0.1	7	1	83
Medical Equipment	1.0	60	7	1,005
Rail	0.3	30	3	374
Total	29.8	7204.0	192.0	132405.0

Figure 2.5: Summary of remanufacturing activity across key European sectors - Adapted from [17]

As illustrated in figure. 2.5, according to the European Remanufacturing Network (ERN)[17], remanufacturing activities within the European Union span a wide range of industrial sectors, such as aerospace, automotive, heavy-duty and off-road equipment (HDOR), electrical and electronic equipment (EEE), machinery, medical devices, rail, marine, and furniture. Collectively, these sectors generate an estimated turnover of 29.8 billion euros, employ around 192,000 people across the EU, and process approximately 132,405 million returned core products. Among these industries, the aerospace, automotive, and EEE sectors constitute some of the most significant contributors in terms of both economic output and employment, underscoring the critical role of remanufacturing across diverse industrial fields.[17]

Within this landscape, the automotive sector accounts for one of the largest proportions of remanufacturing activities [15][17], particularly involving components such as alternators, engines, and transmissions. These components are remanufactured to restore their operational performance while reducing material and energy consumption compared to manufacturing new parts. The high volume of standardized components, together with mature and efficient reverse logistics networks, makes automotive remanufacturing economically viable.

The aerospace sector is also identified by the ERN as one of the largest remanufacturing sectors, primarily through maintenance, repair, and overhaul (MRO) operations. Because of the long service life and high economic value of aerospace products, the processes facilitate the recovery and reuse of high-value components, including engines, avionics systems, and landing gear. Remanufacturing in this sector extends product life cycles while ensuring adherence to stringent safety and certification re-

quirements. The ERN report [17] further notes that aerospace remanufacturing is deeply embedded in the supply chains managed by OEMs. and service providers, thereby enhancing resource efficiency and reducing overall costs.

In the heavy-duty and off-road (HDOR) equipment sector [19] , another of the largest shares of remanufacturing activity is for components used in construction, agriculture, lifting, handling, and mining operations. Remanufactured parts are extended to forklift trucks, cranes, hydraulic pumps, transmissions, and drivetrain modules. Comparably, these are heavy in size and have longer service lifetimes, which emphasizes the importance of component recovery and life extension of the product. Also, considering the size and technical complexity HDOR , equipment creates challenges for remanufacturing processes -related to disassembly, inspection, safety assurance, and component inventory management.

In the remanufacturing of machinery and industrial components, bearings [10] constitute a key area of application. Bearing remanufacturing generally involves two principal stages: analysis and remanufacturing. The analysis stage includes cleaning, inspection, documentation, and the formulation of remanufacturing recommendations, while the remanufacturing stage covers machining, quality inspection, assembly, final inspection, packing, and shipping. The primary goal is to return the bearing to a like-new state, offering comparable quality and warranty to a newly produced component. From an economic standpoint, this approach also helps lower energy consumption and shorten production lead times, thereby reducing manufacturing costs and enhancing resource efficiency, which explains its growing adoption as a viable strategy.

Within the Waste Electrical and Electronic Equipment (WEEE) sector [20], remanufacturing is a core circular-economy practice that focuses on extending product life through reuse. The typical remanufacturing process in this field usually comprises disassembly, cleaning, inspection, sorting, refurbishment, reassembly, testing, and final shipment. Since returned products or cores arrive in varied and often non-standard conditions, these activities are typically very labour-intensive .

In the railway sector [21], remanufacturing is essential for restoring key components such as bogies, axles, and transformers to like a like-new state that meets safety, performance, and reliability standards. These components are typically remanufactured after about 15 to 20 years of operation. The remanufacturing workflow depends largely on the expertise of the operator. The operator assesses the condition of the parts and estimates their remaining service life following remanufacturing. Typical stages in the process include evaluation of returned products, thorough inspection of the cores, and final compliance checks. Since railway components are safety-critical, the operator's judgment is crucial for deciding whether repair is feasible and for ensuring reliability throughout the component's second life cycle.

2.3 Ergonomic Risk Factors In Labour-Intensive Work

Even though Industry 4.0 is increasingly being implemented across industrial sectors, it is still relying on manual operations for some of the stations or work phases, like assembly, material handling, maintenance, and disassembly. In these operations, the operator may be exposed to the risks due to the physical demands of tasks, which negatively affect cognitive performance, physical health, and long-term productivity, which may lead to discomfort and work-related musculoskeletal disorders (WMSDs). So, continuously identifying and evaluating the risk in the workplace contributes to improving workplace safety in manufacturing environments.

The most common ergonomic risk factors in labour-intensive environments are awkward working postures, repetitive motions, application of excessive force, and manual handling[22]. Awkward postures include frequent bending, twisting, reaching above shoulder height, and working in confined spaces, all of which increase biomechanical stress on the muscles and joints of the back, shoulders, and upper limbs. Maintaining these postures for extended periods can lead to a heightened risk of musculoskeletal strain and injury. In addition, repetitive movements sustained over long durations impose cumulative loads on muscles, which can reduce work capacity and elevate the likelihood of injury over time.

Manual handling activities represent another ergonomic challenge in labour-intensive production systems. Tasks involving lifting, carrying, or positioning components often require considerable physical effort, particularly when components are heavy or handled without mechanical assistance. Poorly designed manual material handling systems may therefore contribute to reduced task accuracy and increased injury occurrence, ultimately affecting both worker well-being and operational performance.

In the battery industry [23], the shift toward electric vehicles and e-mobility has increased, as the need for end-of-life treatment of batteries, which can't be fully automated because the returned products are complex and highly variable, makes it challenging to introduce automation, so manual work is still heavily involved in dismantling operations. Consequently, these workplaces are typically labour-intensive and require operators to perform substantial physical loads and awkward body positions, which raises the risk of WMSD. Model-based ergonomic analyses using digital human modeling tools and evaluation methods such as the Ergonomic Assessment Work Sheet (EAWS) have shown that specific dismantling activities, for instance, tray-cover removal, place considerable strain on the upper limbs and could be improved through assistive technologies like industrial exoskeletons [23]. Such solutions can act as interim ergonomic support measures until more advanced automation can be realized.

2.4 Ergonomics In Manufacturing

In manufacturing, ergonomics is an essential approach for optimizing how machines, tools, and workers interact. This leads to higher productivity and a safer work

environment. The primary objective of ergonomic design is therefore to improve workplaces and work processes to human physical and cognitive abilities, and to prevent work-related musculoskeletal disorders(MSDs) by minimizing exposure to risk factors such as awkward postures, repetitive motions, and manual material handling, all while sustaining the production process[24].

Nowadays, in the Industry 4.0 context, the implementation of automation and digitization has made manual labour activities still necessary[13]for some of the workstations and operations. In such operations, workstation layout, operator working postures, and movement patterns affect worker’s well-being and operation efficiency. While ergonomic assessment methods are applied to evaluate the worker’s posture and movement patterns to reduce the risk in the workstation and improve performance [25].

In the context of sustainable manufacturing, Human Factors and Ergonomics (HF/E) represents a key component, shifting industrial priorities in Industry 5.0 toward a human-centered approach rather than a technology and an efficiency-driven one by balancing the environmental, economic, and social well-being across the production.[22].

2.4.1 Ergonomics in the Remanufacturing Industry

The remanufacturing process is distinct from conventional manufacturing primarily because the condition of returned products is uncertain. The returned components arrive with different levels of wear, damage, corrosion, and contamination. Because of this variation, it is very difficult to follow one fixed work procedure as the operators may need to change the task sequence, use different tools and equipment, apply varying levels of force, or adjust their working posture depending on the product’s condition[18]. Since many remanufacturing activities still depend heavily on manual work with an operator’s cognitive skills and judgment, ergonomic conditions become a crucial factor[21].

The body of literature that directly explores the relationship between remanufacturing and ergonomics is relatively small. Most studies focus on specific products, industries, technologies, or individual tasks. There is still limited research that compares ergonomic exposure across different remanufacturing work phases, such as disassembly, cleaning, inspection, reprocessing, and reassembly. There are also relatively few studies that combine real remanufacturing task conditions with structured ergonomic assessment methods and digital human modelling. This creates a need for further research to identify which work phases are most physically demanding, what types of ergonomic risks are present, and how digital assessment methods can support safer and more human-centred remanufacturing workstations. Existing studies typically concentrate on particular tasks, including manual remanufacturing operations, workcell configuration, or the processing of returned parts and their restoration techniques[20]. Also in contrast to the broader field of manufacturing ergonomics, only a limited number of investigations discuss how the inherent uncertainty and variability of remanufacturing activities influence workers’ posture, physical demands, and long-term well-being[26].

Among the existing studies, manual disassembly is identified as one of the main areas

of ergonomic risk concern within the remanufacturing work phases. The returned products may contain damaged, corroded, or difficult-to-access and extract parts, which can make component removal more demanding. Operators may need to bend, stretch, reach, use hand tools repeatedly, or apply additional force to separate these parts. The physical demands can become even higher when the product was not originally designed for easy disassembly and the absence of a standard working procedure, or when suitable tools and fixtures are not available[18].

Based on the studies about WEEE remanufacturing, it is emphasized that ergonomic analysis should be considered during the design of remanufacturing workcells. Digital mock-up methods using CAD and human modeling software to be used for disassembly sequences, to study how the operators interact with fixtures and components, and to support changes that improve performance and accessibility within safe working conditions[20]. This indicates that ergonomic risks in remanufacturing are linked not only to the nature of the task itself, but also to improved workstation layout, how components are positioned, and how the product is supported during manual operations. Taking ergonomic aspects into account during the disassembly phase, when components are dismantled, can affect body posture, reaching distances, necessary exertion of force, and overall physical workload, thereby helping to lessen operator strain before issues arise in the workplace[23].

2.5 Ergonomic Assessment Methods

Ergonomic assessment methods are essential instruments used to identify and quantify physical workload and postural stress in workplaces such as manufacturing and healthcare. They support the analysis of work tasks, facilitate the identification of risks associated with specific activities performed during those tasks, and assist in implementing preventive measures to reduce WMSDs and enhance workplace safety [24].

Ergonomic assessment methods are generally divided into three categories:

- Observational
- Biomechanical
- Digital simulation-based [24]

Among these, observational methods are the most frequently applied in industrial or manufacturing settings because they are straightforward and easy to use. Tools such as the Rapid Upper Limb Assessment (RULA)[27] and the Rapid Entire Body Assessment (REBA)[28] are widely employed to evaluate postural risk by examining body positions, applied forces, and movement repetition. These methods offer a fast estimation of ergonomic risk levels and are particularly effective for identifying high-risk tasks in manual operations. Furthermore, the Key Indicator Method (KIM)[29]

is utilized to evaluate manual handling activities, including lifting, pushing, pulling, and carrying. In KIM, factors such as load weight, posture, frequency, and duration are taken into account. The Ergonomic Assessment Work Sheet (EAWS)[30] provides a comprehensive evaluation by integrating various risk factors, including body postures, action forces, manual material handling, and upper-limb activities.

EAWS is extensively used in manufacturing environments because it delivers a detailed assessment of physical workload and is well-suited to industrial applications, but it requires competent training and a license[30] .

These assessment techniques are highly relevant to labour-intensive remanufacturing processes, where tasks such as disassembly and the handling of heavy components expose workers to considerable physical demands. In remanufacturing, the variation in products and the high level of manual work mean that operators are often exposed to awkward postures, repetitive motions, and substantial force exertions. The application of e.g, RULA, REBA, KIM, and EAWS enables practitioners to identify high-risk activities and supports the development of targeted ergonomic interventions, including workstation redesign, process improvements, and the adoption of assistive technologies.

However, these ergonomic assessment methods largely depend on observational judgments and relatively simple scoring schemes, which may not fully represent complex working conditions. Consequently, combining several assessment approaches and incorporating advanced tools such as digital human modelling can enhance the precision and overall comprehensiveness of ergonomic evaluations in contemporary manufacturing systems.

3

METHODOLOGY

This chapter describes the methodology in this study, outlining the techniques chosen and their implementation to address the research case. It provides a clear overview of how each phase was systematically planned and executed.

3.1 Visualization & Description of Methodology

Figure 3.1 shows a visualization of the methodology that was followed in the thesis research. At the beginning of the research, a knowledge foundation was established with an literature study, combined with prior knowledge, which helped help understand the existing body of work and identify key gaps that the research aims to address[15]. While the thesis focuses on the connection between remanufacturing and ergonomics, the literature study was used to understand both areas and for the development of a suitable research methodology.

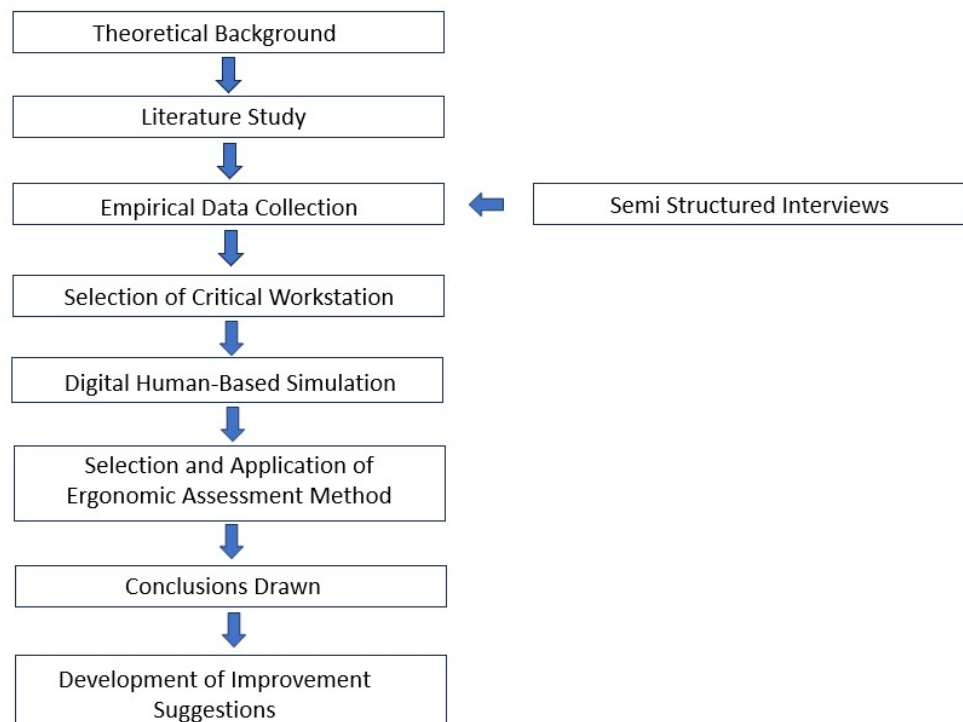


Figure 3.1: Visualization of Methodology

The next step was data collection, relevant data were gathered by conducting semi-structured interviews[31] with industry-based experts and other external stakeholders, such as Professors, Ph.D. students related to remanufacturing and ergonomics. This allowed for more understanding of the issues by capturing different perspectives. The interviews were designed to explore remanufacturing workstations, challenges, and insights of the stakeholders, contributing valuable qualitative data to the study. After the data collection, the next phase was to analyse the information to extract valuable insights. The data collected from the literature study and interviews are helpful for key findings relevant to the research objectives.

After identifying the critical workstation, a simulation scenario was designed using the software Intelligently Moving Manikin (IMMA)[32]. The simulation scenario was designed on the basis of expert interviews, and the critical remanufacturing workstation was selected. The simulation scenario included manual disassembly tasks, which involves gaining access to the product and disassembling components. So, through this simulation scenario, the operators were studied digitally.

Once the simulation scenario was designed, an ergonomics assessment approach was selected and used to identify and analyze the critical risk factors associated with the selected workstation. The aim of the ergonomic assessment was to determine and analyze the ergonomic risks involved in the workstations having high risk factors associated with them.

The findings of the ergonomics evaluation and simulation evaluated and a conclusion was derived. Guidelines for ergonomic improvements we suggested for the workstation risks. The objective of these guidelines is to improve the ergonomic situation for manual remanufacturing operations.

3.2 Research Design

The study used a sequential mixed-method[33] approach, beginning with qualitative exploration to understand current remanufacturing operations and ergonomic conditions in workstations, followed by quantitative assessment to measure identified risks and support improvement strategies.

- Data collection Phase: The initial phase involved conducting a literature study and semi-structured interviews to gather comprehensive data on the current state and to understand how remanufacturing works and ergonomic conditions in remanufacturing workstations.
- Simulation Phase: This phase involves developing a Digital Human Modeling simulation case for the selected remanufacturing workstation. This was done on the basis of expert input, task descriptions, and working postures.
- Analysis Phase: The second phase applies ergonomic risk assessment methods[24] (e.g., RULA, REBA, KIM ,EAWS[27, 28, 29, 30]) to quantify identified risks and develop corresponding improvement strategies.

3.3 Literature Study

The literature study established the thesis's theoretical foundation, and it focused on knowledge about circular economy, remanufacturing processes, workplace ergonomics, risk factors in manual work, and ergonomic assessment methods, particularly in remanufacturing workstations.

Consequently, the review was not limited only to directly matching studies. Instead, it was structured around related areas that were relevant to the topic. This approach was necessary because human participation, workstation conditions, and ergonomic constraints were all associated with manual disassembly and remanufacturing activities, where manual disassembly was affected by both environmental and ergonomic limitations.[34]

The first part of the literature study focused on remanufacturing to understand its main characteristics, work phases, and operational challenges. This helped explain how remanufacturing differed from conventional manufacturing, especially due to the uncertainty or variability of returned products and the labour-intensive[14] nature of activities such as disassembly, inspection, cleaning, repair, and reassembly. Understanding these characteristics was important because they influenced the physical demands placed on workers.

The second part of the literature study focused on ergonomics in manufacturing and other manual industrial environments. Even if literature was not specifically carried out in remanufacturing settings, it was considered relevant because many of the work-related physical demands were similar. Tasks involving awkward postures, repetitive movements, manual handling, forceful exertion, and tool use were common in many industrial environments and were also expected in remanufacturing workstations. Therefore, this body of literature provided useful knowledge for identifying possible ergonomic risks in the studied context.

The third part of the literature study focused on ergonomic risk assessment methods that were suitable for analysing industrial work tasks. In this study, particular attention was given to assessment tools such as RULA, REBA, and KIM, since these methods are commonly used to evaluate posture-related risks, whole-body loading, and manual handling activities. Reviewing this literature was necessary to support the selection of an appropriate ergonomic assessment method for the thesis. Overall, the literature study was based on combining these related areas of knowledge rather than relying only on studies that directly matched the exact thesis topic. This approach was necessary because of the limited number of studies at the intersection of remanufacturing and ergonomics. At the same time, this limitation also highlighted a research gap, which further supported the relevance of the present study.

3.3.1 Database Search

The literature study was carried out using a search strategy across scientific databases and search platforms such as Scopus and Google Scholar, while the Chalmers library was used as a resource, ensuring access to relevant and peer-reviewed research articles, conference papers, books, and other scholarly sources. These databases were selected because they covered literature related to remanufacturing, production engineering, ergonomics, and manufacturing systems. To identify relevant studies, different combinations of keywords were used during the search process. These included terms related to remanufacturing, ergonomics, workstation risk factors, manual handling, awkward posture, repetitive work, and ergonomic assessment methods. Since the direct overlap between remanufacturing and ergonomics turned out to be limited, broader keyword combinations were also used to capture studies from related industrial contexts.[26]

3.3.2 Inclusion & Exclusion Criteria

To ensure the relevance of the selected literature, inclusion and exclusion criteria were applied during the review process. Studies were included if they addressed remanufacturing processes, labour-intensive industrial tasks, ergonomic risks in manual work, or ergonomic assessment methods applicable to industrial settings. Literature related to manufacturing, assembly, disassembly, and other comparable manual work environments was also included when it contributed useful knowledge for understanding ergonomic exposure.

Studies were excluded if they focused on areas that were not relevant to the research scope. Sources with limited methodological clarity or weak relevance to workstation analysis were also excluded. In addition, emphasis was placed on sources available in English and in full-text form.

3.3.3 Screening Strategy

The screening of literature was carried out in a step-by-step manner in order to maintain a structured review process. First, search results were collected from the selected databases based on the chosen keywords. Second, titles and abstracts were reviewed to identify whether the studies were relevant to the research topic. At this stage, clearly unrelated studies were removed. Third, the remaining sources were assessed through full-text reading in order to evaluate their contribution to the thesis and their suitability for the study.

After the screening process, the selected literature was organized into thematic areas. These themes included remanufacturing process characteristics, ergonomic risk factors in manual industrial work, and ergonomic assessment tools. Organizing the literature in this way made it easier to connect the theoretical foundation to the research problem and to justify the methods used later in the study.

3.4 Semi-Structured Interviews

Semi-structured interviews[31] were used as one of the qualitative methods in this study to get a deeper understanding of remanufacturing work practices and the ergonomic challenges experienced in daily operations in the workstations. Since the purpose of the thesis was to identify ergonomic risks in labour-intensive remanufacturing workstations and develop improvement strategies, it was important first to understand how the work was actually performed, how workers experienced it, and which tasks were perceived as the most physically demanding. The interviews were intended to provide insights into real remanufacturing tasks, work routines, awkward postures, repetitive movements, manual handling, and the influence of operational pressures such as time constraints and productivity targets. This made the interview phase an important step in building a practical understanding of the work environment before moving into direct observation and risk assessment.

The interviews were conducted offline or onsite and online, depending on the stakeholder's convenience. The information was extracted and documented through permitted audio recordings and associated transcripts.

3.4.1 Participant Selection

Participants for the interviews were selected based on their relevance to the remanufacturing process and their practical knowledge of the work under study. In this case, the most suitable participants were managers and personnel directly involved in remanufacturing activities, such as disassembly, cleaning, inspection, reconditioning, and assembly[4]. In addition to operators, other relevant participants included supervisors, team leaders, engineers, researchers, ergonomists, or other stakeholders who had a broader understanding of the workstations and their challenges. The participants were chosen because they could contribute relevant information to the research questions. Since the study aimed to identify which work phase or work zone contained the highest ergonomic risks, it was useful to speak with people from different stages of the remanufacturing process so that comparisons could be made across tasks and workstations.

The intention was to include participants who could provide both hands-on and process-level perspectives on how the work was carried out and where ergonomic problems were most likely to occur. This followed the direction where interviews were used to collect perspectives from company personnel and other knowledgeable stakeholders in order to identify the work phase with the highest ergonomic risk exposure. In this way, the interviews helped ensure that the later simulation-based study focused on the most relevant area.

3.4.2 Interview Guide

The interview guide was developed around the overall aim and research questions. Instead of using a fixed list of questions, the interviews followed a semi-structured format, as in Appendix A. This meant that key themes were prepared in advance,

but follow-up questions were also asked depending on the participant's role and responses. This approach was suitable because it allowed participants to speak more about their work and experiences, while still keeping the discussion focused on the topics that were important for the thesis.

The guide covered areas such as the participant's role and experience, the tasks performed during a typical work shift, the most physically demanding or time-consuming activities, and the work phases that were perceived as the most ergonomically challenging. Questions also explored awkward postures, repetitive movements, lifting and handling activities, the use of tools, workstation layout, and any discomfort or fatigue experienced during work. In addition, the interviews examined whether operational pressures such as deadlines, productivity demands, or lack of time influenced how work was performed.

3.4.3 Data Analysis Method

The collected interview data were subjected to a qualitative analysis approach to attain insights into the remanufacturing process, workstations, and ergonomic issues. The collected information was analyzed to make proper alignment with the research study and classified into categories. These related to ergonomic considerations such as awkward postures, repetitive work tasks, and also to the process included.

3.5 Simulation-Based Study

Digital human simulation has been emphasized as a valuable tool for workplace design and ergonomics validation, especially for assessing ergonomic risks during the design of assembly and disassembly operations. Following the literature review and the semi-structured interviews, a simulation-based study was conducted. The insights gained guided the selection of the specific work phase to be modeled with Digital Human Modeling, based on its anticipated ergonomic risks. Accordingly, the ergonomic analysis was performed using Digital Human Modeling (DHM) in IPS-Intelligently Moving Manikin (IMMA) software[32] and the associated ergonomic risks were assessed in a structured manner in the software. The interviews clarified the key phases of remanufacturing work, including disassembly, cleaning, inspection, repair, and assembly.

3.5.1 Selection of Remanufacturing Workstation and Phase

Among the phases detailed in Chapter 2, the disassembly phase was chosen for the simulation study. This decision was based on findings from the semi-structured interviews and its strong link to manual tasks that are subject to ergonomic risks. A key reason is the variability of returned cores (which differ in wear, condition, and damage). The literature [14, 34] also supports this conclusion, indicating that traditional disassembly processes are predominantly manual and labour-intensive. Consequently, disassembly was well-suited for a simulation-based assessment, as it frequently involves awkward postures, bending, tool use, and manual material handling. The selected

disassembly task was therefore used as a simplified yet realistic case for identifying ergonomic risks.

3.5.2 Scenario Description

For the simulation, the manual disassembly of an industrial demolition robot was chosen. The simulation scenario was designed using information obtained from the industry expert (case scenario developed from Husqvarna[35]) and the reference product as in Figure 3.2. The scenario and related details highlighted disassembly as a physically demanding task in remanufacturing. During this process, the operator frequently had to handle heavy components, work at a low height, and reach into tight spaces within the machine. In addition, components were often difficult to remove due to prolonged use.



Figure 3.2: Reference Product for the Scenario

The simulated workstation was designed to mirror a realistic remanufacturing setting. The industrial demolition robot as in Figure 3.2 was assumed to be placed at a low working height, with restricted space surrounding the work area. Tools were assumed to be located on a nearby side table. The simulation included uncomfortable working postures, manual lifting and carrying, high force requirements, repetitive motions, long reaching distances, reduced accessibility in the workspace, and potential work errors resulting from fatigue, poor visibility, or constrained workstation layout.

3.5.3 Task Breakdown

In the task breakdown, the disassembly simulation scenario is divided into smaller sub-tasks. This was necessary to identify the movements, reach requirements, and handling actions that needed to be represented in the simulation.

The scenario described here was not derived from direct workplace observation, but was instead based on details gathered during semi-structured interviews and subsequent follow-up questions with industry experts. During these interviews, it was repeatedly emphasized that the disassembly phase is physically demanding and should therefore be used as the basis for the simulation.

The scenario outlined below concentrates on the following key activities: removing the front cover, disassembling the motor and associated parts, and lifting and transporting heavy components.

- Removing bolts: This task was selected because, before reaching into the internal parts like the motor, the operator needs to exert a significant force to remove the external cover. It involves the loosening of the nuts with allowable torque combined with handheld tools. Here, the possibility of repetitive tasks while loosening the bolts and awkward postures was examined on the asymmetric loading when the operator supports a panel cover, leaning body weight on the panel cover.
- Extraction of heavy components and dismantling parts: After removal of panel covers, the operator eases up small internal connections fitted with certain components such as motor, valve blocks, and accumulators by disconnecting their respective hydraulic hoses, clamp fittings, and similar joints. The main heavy components are extracted. As in the case of a motor, after extraction, its sub-components, such as seized or damaged rotors, are manually removed from the stator body with forceful exertion in the operator's wrists, arms, shoulders, and back.
- Lifting and transporting of heavy parts: The extracted and dismantled parts are transported from the disassembly station for inspection and cleaning. Trolleys were utilized by the operator for this task, with extra force added for transferring the heavy components. Handling a load far from the body subjects workers to a physical strain in the lower back and shoulders.

3.6 Ergonomic Risk Assessment Procedure

The ergonomic risk assessment procedure can be considered the quantitative component of the methodology. DHM was developed and then evaluated using established ergonomic assessment tools (REBA and RULA).

In addition, the study contrasts the simulation-based assessments with those from KIM, where this comparison was feasible. KIM was selected as the ergonomic assessment approach because the Swedish Work Environment Authority provides and recommends KIM for evaluating risks related to manual handling and physical workload. In particular, KIM:LHC [36], KIM:MHO[37], and KIM:PP[38] address lifting and carrying and repetitive manual handling tasks. Consequently, KIM was well suited for comparing manual handling risks against the DHM-based assessments used in this thesis.

3.6.1 Tool Selection Criteria

The right selection of ergonomic assessment tools will depend on the type of each simulated task. The task breakdown, force assumptions, and posture conditions were used to decide which assessment method was most suitable for each scenario.

REBA was used for tasks involving whole-body posture, applied force, grip condition, and body stability, like pulling or handling components. RULA was mainly for tasks involving upper-limb posture. Although the method EAWS was included in the software, correct usage requires extensive training and a license, which were considered out of scope for this thesis.

KIM methods consider a wider range of workplace-related factors than RULA or REBA do, and the lower level of detail in assessing posture in KIM is compensated for by also assessing the proportion of time spent on the task during a work shift, repetitiveness, environmental conditions, and separate scores are calculated for men and women respectively.

3.6.2 Scoring and Comparison

The scoring depends on the postures, force inputs, grip conditions, and task characteristics from the DHM scenarios. For RULA and REBA, we looked at the relevant body parts—like the neck, trunk, legs, upper and lower arms, wrists, and shoulders—in the simulated posture.

With KIM, the focus shifted to factors related to manual handling, such as load, posture, movement conditions, how long tasks took, and whether they were repetitive. Afterward, KIM results got compared with those from the DHM-based assessments when possible.

Finally, these scores helped classify the ergonomic risk level for every task. This process helped spot problem areas in the body, see how posture-based risks compared to those from a wider analysis with KIM, and suggest ways to make improvements at the remanufacturing workstation.

4

RESULTS

This chapter highlights the findings of this thesis work.

4.1 Literature Findings

The detailed result of the Literature review summarized throughout the chapter 2.

The literature study summarized below:

Remanufacturing plays an important role under current conditions, as it prolongs the service life of used products. Instead of being discarded after use, they are restored through remanufacturing to a condition that is close to new. This process helps reduce the consumption of resources and energy, while preserving product value [15]. Remanufacturing typically consists of a series of steps, including disassembly, cleaning, inspection, repair, replacement, and reassembly [15, 4].

The process is inherently labour-intensive, as it begins with used products or core that vary in condition and types of damage, which means a substantial share of the work must be performed manually. This aspect underscores that people and human labour are central elements of the remanufacturing process [15].

In some remanufacturing settings, decision-making is delegated directly to the operator [21]. The operator's diagnostic skills are employed to assess components and decide whether they can be repaired or should be reintegrated in their current state into the remanufacturing flow. This shows that remanufacturing activities place demands not only on physical effort, but also on cognitive capabilities.

Disassembly is widely regarded as a critical and challenging phase of remanufacturing due to the variability of returned products. This variability affects operational planning in various industrial environments and across different product categories. Disassembly is generally labour-intensive and time-consuming, especially given the diverse states in which cores are returned. As a result, ergonomic issues may arise during the execution of these tasks [20, 34].

The main ergonomic risk factors reported in the literature include awkward working postures, manual material handling, high force exertions, and repetitive motions. These risks are linked both to the variability of the returned cores and to the inherent characteristics of disassembly and component evaluation throughout the remanufacturing process [34, 20, 23, 4].

Therefore, the findings indicate the need for ergonomic assessment to identify and evaluate the physical risks associated with manual and labour-intensive remanufac-

turing tasks.

The findings from the literature can be outlined in the following way, showing how the conclusions were developed and linked together, as shown in Figure 4.1

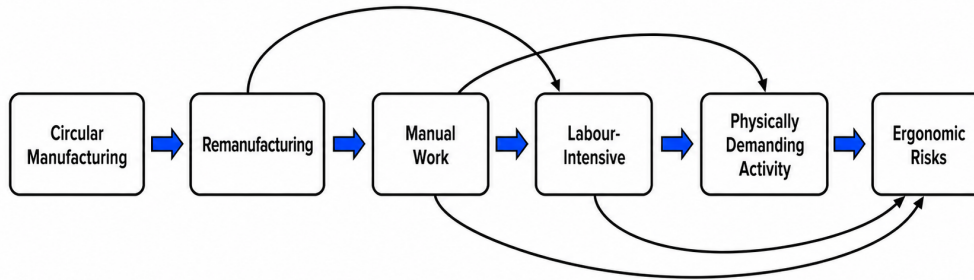


Figure 4.1: Logic structure of literature findings

4.2 Outcomes From Interviews

4.2.1 Interview Participants

The participants comprise a blend of academic and industry professionals, including staff from remanufacturing companies, an ergonomics specialist, and university researchers. All participants were informed that it was for academic purposes and consented to the use of their responses.

Table 4.1: Interview participants

Code	Organisation	Role/Background	Relevance to the Study	Interview Type
I1	SKF-Reman	Business Development Manager	Remanufacturing process knowledge	On-site
I2	Feelgood	Ergonomics representative	Ergonomic risk and worker safety knowledge	Online
I3	Husqvarna	Application Specialist Light Demolition	Workstation and process knowledge	Online
I4	Chalmers University Of Technology	Academic Professor	Remanufacturing and ergonomics perspective	On-site
I5	Chalmers University Of Technology	PhD candidate	Research knowledge in remanufacturing	On-site
I6	KTH Royal Institute of Technology	Postdoctoral researcher	Re-Remanufacturing perspective	Online

4.2.2 Summary of Interviews

The interview responses were summarized below. The summaries present the main points from each interview while keeping the participants identities protected.

Interview (I1) - Business Development Manager/SKF-Reman

The interview and onsite visit offered valuable insight into the industrial remanufacturing background. The interviewee explained that bearing remanufacturing is a multi-stage process that includes cleaning, washing, analysis or inspection (diagnosing the bearing to determine whether remanufacturing is feasible), disassembly, machining (such as honing and hard turning), repair, and final assembly. An important takeaway from the interview was that the most physically demanding stage differs depending on the specific product and process conditions.

In SKF's bearing remanufacturing, machining was highlighted as a particularly labour-intensive step, illustrating that ergonomic risks cannot be assumed to be uniform across all remanufacturing activities. The interview also outlined existing ergonomic management practices, such as internal guidelines developed by SKF and the workers' union, daily morning meetings, issue reporting by employees, and collaboration with an external ergonomics partner. This indicates that structured ergonomic routines may be embedded at the organizational level in mature remanufacturing environments.

At the same time, the interview revealed that formal, task-level ergonomic assessment tools like RULA, REBA, or KIM had not been systematically implemented at remanufacturing workstations. Ergonomics was explicitly linked to operational outcomes: improved ergonomic conditions were associated with lower sick leave, higher quality, and increased productivity. Automation and digitization were also identified as long-term strategies for enhancing and expanding remanufacturing operations.

Interview (I2) – Ergonomics Representative

The interview offered insights from a professional ergonomist. The interviewee highlighted repetitive motions, awkward working positions, and manual handling of materials as the main ergonomic risk factors. They also pointed out that workstation layout, the placement of tools, ease of access to components, and a lack of task variation all play significant roles in creating physical strain.

An important message from the interview was that working correctly should be made easy for employees. In practice, this means that safe postures should not rely solely on individual behavior, but must be actively supported by the design of the workstation. The interview further stressed that ergonomic evaluations should be integrated early in the process, rather than being carried out only after issues have already appeared.

The interviewee referred to QEC (Quick Exposure Check) and the latest versions of KIM as relevant tools for ergonomic assessment, noting that the choice of method should be guided by the type of task, how it is performed, and its frequency. Variation in posture was underscored as a key principle for improvement. Employees

should be able to alternate between standing, sitting, walking, resting, and moving throughout the workday. This variability was linked to lower fatigue, improved alertness, fewer quality defects, less rework, and reduced sick leave.

Interview (I3) - Application Specialist Demolition /Husqvarna

The interview offered practical industrial perspectives on refurbishment activities related to remanufacturing. The interviewee outlined robot remanufacturing refurbishment as a multi-stage process that includes inspection (diagnosing to assess whether remanufacturing is viable and identifying the required work), disassembly, cleaning, repair, restoration, assembly, testing, and quality control.

The interviewee characterized disassembly and assembly as challenging, physically demanding phases. Disassembly may involve corroded or hard-to-reach parts, which can demand repeated use of tools and considerable physical effort. Such conditions can cause strain and discomfort in the back, shoulders, and wrists. Cleaning was also described as a time-intensive task. In some situations, cleaning must be carried out multiple times when additional contaminated areas become visible as the process progresses. The interview further highlighted that time pressure can affect ergonomic behavior: under tight deadlines, workers may opt for quicker methods that are not always ergonomically appropriate.

The interview indicated that ergonomic evaluations are systematically carried out at workstations through internal safety procedures, observational checks, and team discussions. Ergonomics was presented as a long-term investment in operations. Suggested measures to reduce fatigue and enhance work quality included better tools, height-adjustable workstations or tables, improved task planning, and combined disassembly–cleaning stations. Ergonomic enhancements were also associated with lower error rates, improved lead times, and overall better operational performance.

Interview (I4) - Academic Professor /Chalmers

This interview provided an academic point of view on remanufacturing. Drawing on observations made during site visits, the interviewee emphasized that disassembly represents a major ergonomic challenge in remanufacturing. A primary reason given was that operators frequently rely on general-purpose hand tools that are not tailored to the geometry of specific components or products. As a result, higher exertion of force is often required, which can promote awkward working postures.

The interview reinforced the understanding that ergonomic risks in remanufacturing are shaped by the characteristics of the task, the suitability of the tools, and how easily products can be accessed. When tools are not well matched to the task, operators may compensate by exerting more force or by working in suboptimal postures.

The discussion also underscored the importance of investigating ergonomics specifically within the context of remanufacturing. The link between ergonomics and remanufacturing was characterized as an area that still requires further attention. Improving tooling emerged as a key practical avenue, as task-specific tools could lower force demands and enhance working conditions.

Interview (I5) - PhD Candidate in Chalmers

This interview provided a research-oriented perspective on remanufacturing and its connection to ergonomics and sustainability. The interviewee described remanufacturing as a process that relies heavily on manual work and has a lower level of automation compared with conventional manufacturing. A key point was that returned products often vary in condition, which makes the work less predictable and requires operators to adapt their posture, tools, and working method.

Disassembly was highlighted as one of the most physically demanding phases. The interviewee explained that operators may need to bend, stretch, reach, or work in awkward positions depending on the product condition and workstation setup. Variability was also identified as an important reason why ergonomic standardization is difficult in remanufacturing.

The interview also connected ergonomics with the long-term sustainability of remanufacturing. Skilled workers and tacit knowledge were described as important for successful remanufacturing operations. Poor ergonomic conditions may increase fatigue, discomfort, and staff turnover, which can weaken the long-term capability of remanufacturing systems.

Interview (I6) - Postdoctoral Researcher /KTH

This interview provided a research oriented perspective on remanufacturing, with emphasis on digitalisation, workflow maturity, and product lifecycle information. The interviewee explained that remanufacturing often lacks the automation, standardisation, and data support available in new manufacturing. This creates uncertainty during inspection, disassembly, and repair because operators may not know the previous use history or condition of returned products.

A major point was that ergonomic risks are not caused only by workstation design. They are also influenced by the structure of the remanufacturing process itself. When product information is missing and workflows are unstable, operators are forced to perform reactive and improvised work. This can lead to unpredictable manual handling, awkward postures, and additional physical effort.

The interview also emphasized digitalisation and lifecycle data as long-term improvement opportunities. Better information about returned products could reduce uncertainty before work begins and make the remanufacturing process more predictable. This can support safer work methods, better planning, and reduced physical strain.

Overall - Interview Summary

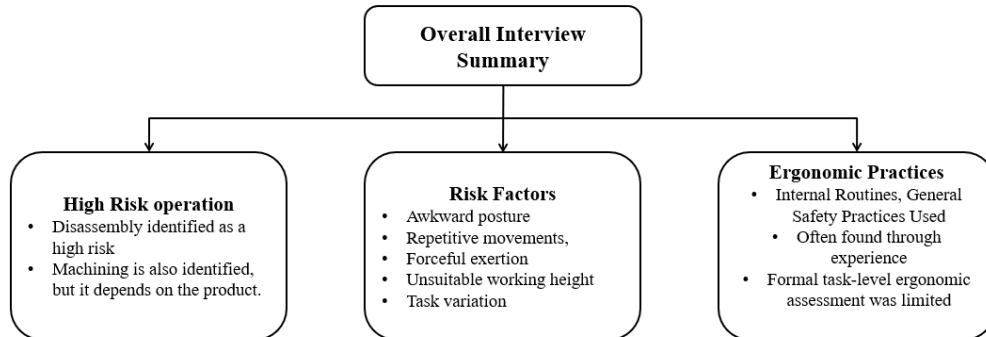


Figure 4.2: Overall Interview Summary

As summarized in figure 4.2, across the interviews, remanufacturing was described as a labour-intensive and variable process. Disassembly was identified as the most high-risk station, although the SKF interview showed that machining can also become highly labour-intensive depending on product type and process context. The main ergonomic risks identified were awkward postures, repetitive movements, forceful exertion, poor accessibility, unsuitable working height, and task variation. The interviews also showed that ergonomic issues are often recognized through experience, internal routines, or general safety practices, while formal task-level ergonomic assessment is limited. This supports the need for more structured assessments of remanufacturing workstations using assessment tools for posture, repetition, and other activities.

Finally, the interviews connected ergonomics with both worker well-being and operational performance. Better ergonomic conditions can reduce fatigue, reduce rework, lower sick leave, improve productivity, and strengthen the long-term sustainability of remanufacturing operations. Ergonomics should therefore be treated as an important improvement area for labour-intensive remanufacturing systems.

4.3 Simulation Analysis

Simulation was used for modeling the manual disassembly process in a remanufacturing station using IPS-IMMA[32] software. This disassembly process entailed an operator disassembling a demolition robot located on a table. The work steps that were modeled through the simulation process included removing bolts for dismounting the front cover, accessing the interior part, removing the rotor from the stator, and manually transporting a heavy part. The image 4.3 shows the setup of the workspace and manikin.

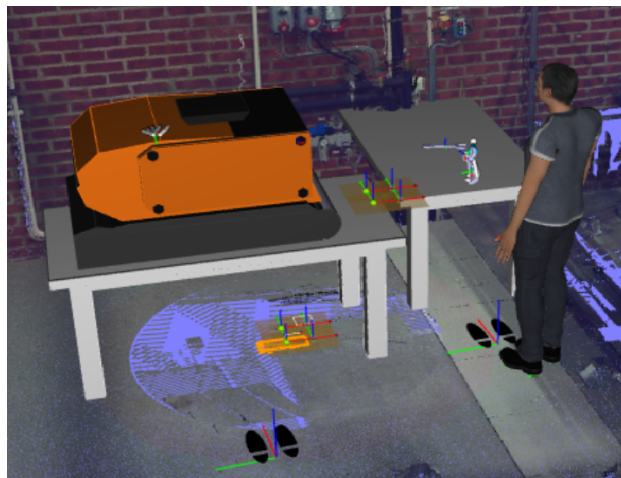


Figure 4.3: Setup of the Workspace and Manikin

The manikin was given assumed gender, weight, and height values. To run the simulation software, it is essential to add a few parameters with certain functions, motion constraints, and validate the operation sequence conditions to make a credible simulation case, followed by evaluating with appropriate ergonomic assessment methods built into the software - in this case, RULA or REBA.

4.3.1 Scenario 1

Figure 4.4 illustrates the manikin positioned beside the machine as it begins to remove the bolt. The machine is situated on the worktable, while the tools are arranged on a separate table.



Figure 4.4: Manikin near the machine, removing the bolt

4.3.1.1 Scenario Description, Assumptions & Calculation

While creating the scenario, the manikin's movements and actions were constructed for loosening the bolts of the panel cover with a torque in correlation with the bolt size, as mentioned in the European standard metric bolts under ISO 898-1 and DIN standards [39]. The values for the forces acting on the right-hand tool operation and left hand supporting the panel cover are calculated based on the force and torque relations as described in EN 1005-3:2002+ A1:2008, which explains the guidelines to manufacturers for the safety of machinery and its parts, human physical performance, and recommended force limits for actions during machinery operation[40].

Table 4.2: Parameter inputs and assumptions for Scenario 1

Parameter input	Value	Description
Bolt size	M12	Assumed the bolt used for tightening the cover
Spanner length	0.24 m	Assumed lever arm length of the spanner
Right hand: Constant force 2	110 N	Force applied by the right hand on the spanner during task
Equivalent loosening torque	26.4 Nm	Calculated using $T = F \times L$, where $F = 110$ N and $L = 0.24$ m
Left hand: Constant force 2	50 N	Assumed force applied by the left hand on the machine body for stabilizing the posture
Force application	One-hand operation	The right hand was used during operation, while the left hand was only for support

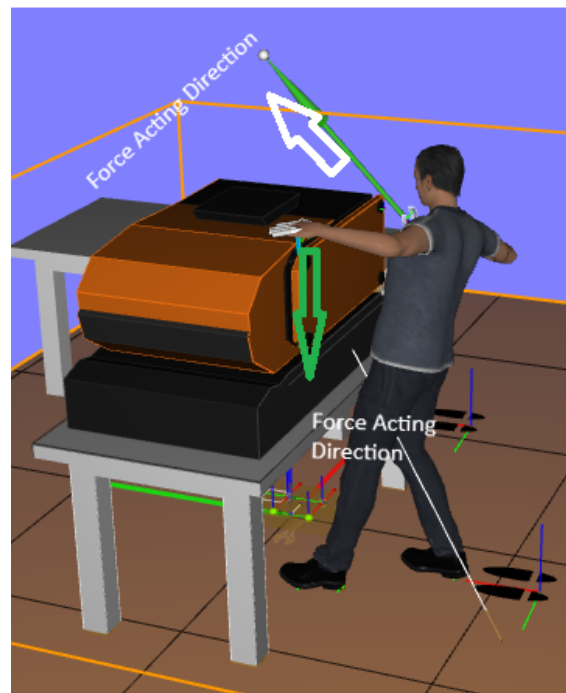


Figure 4.5: Forces in Scenario 1 during the DHM simulation

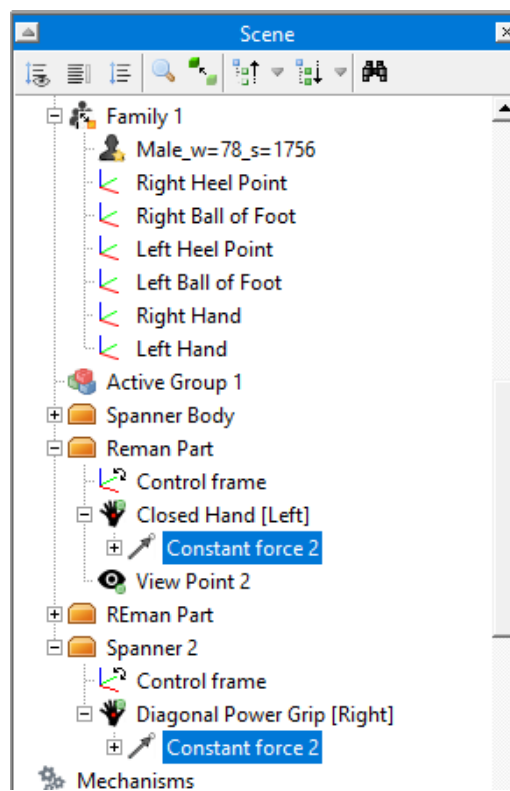


Figure 4.6: Force inputs assigned to Scenario 1

4.3.1.2 Ergonomic Assessment Result

For scenario 1, the REBA-based assessment method was the most suitable option, as it considers whole-body posture and movement when manually using a spanner to loosen components, requiring additional force in the arms and wrists for gripping, followed by a shift in body posture and balance.

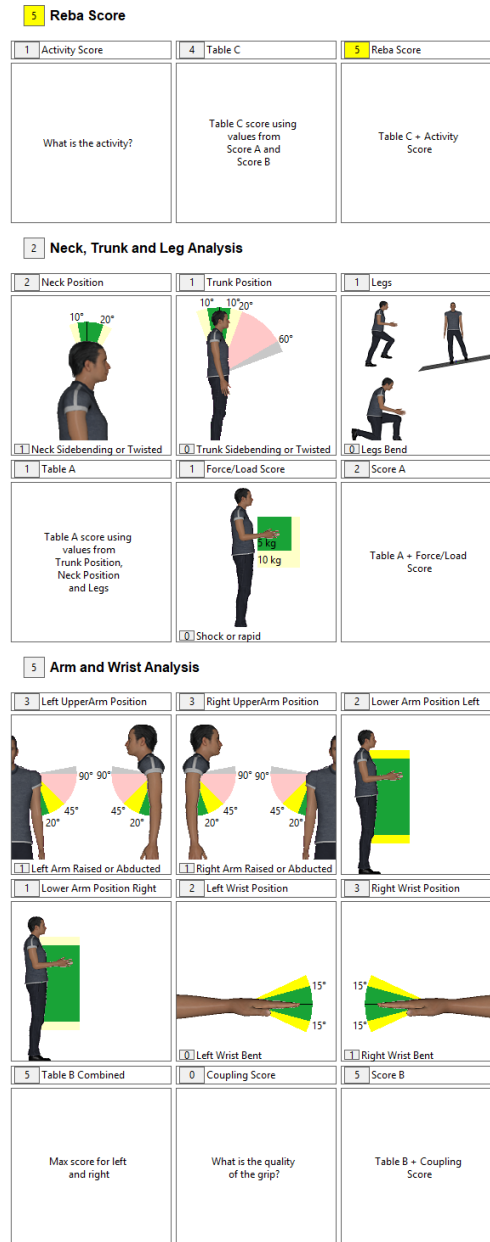


Figure 4.7: Scenario 1 : REBA result from the simulation software.

Figure 4.7 shows the final score as 5, indicating a medium ergonomic risk. Although the task is not critical, it can lead to an increased risk of physical strain when it is prolonged over time with repetition. The score highlights the strained conditions while keeping the arm raised; the waist gets bent when loosening the bolts with the

right hand using a spanner, and inclining the upper body forward to reach the bolts. These account for force exertion over the wrist, arm, shoulders, and neck.

The ergonomic risk can be lowered by using a pneumatic or battery-charged tool in place of a manual handheld tool, and adjusting the work height, and reducing the sub-activity duration.

Modifications help lower the REBA scores associated with: neck, upper arms, and wrist, as well as force/load and activity. Correcting working height would reduce trunk forward bending of neck and make it possible for the arm above the elbow to get closer to a neutral position. Pneumatic or battery-actuated tools would lessen the manual force required from the right hand and reduce load on the wrist and arm. Reducing the time and frequency of the task would cause scores for the activity component to decrease.

4.3.2 Scenario 2

Figure 4.8 shows the workspace for Scenario 2. In this scenario, the manikin is in front of the worktable removing the rotor from the stator. The whole component is placed on the table surface, and the operator uses both hands to grip and pull the component during the simulated operation. This setup was used to evaluate whole body posture, hand grip, and force application during the pulling task.

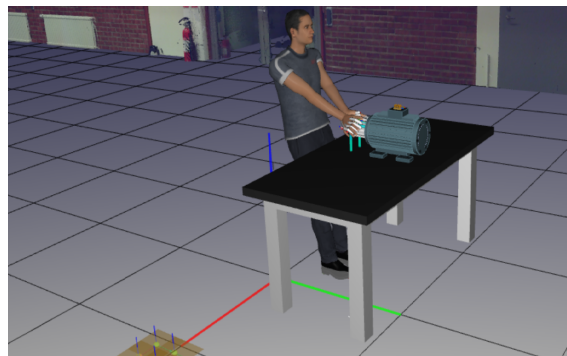


Figure 4.8: Manikin Removing the rotor from the stator

4.3.2.1 Scenario description, Assumptions & Calculation

The task requires the operator to grip the component with both hands and apply pulling force to separate or remove it from its fitted position.

The force values and assumptions used for Scenario 2 are in Table 4.3 .Figure 4.9 and Figure 4.10 shows the force applied in the scenario. These values are assumptions for the DHM simulation. The actual force required during real disassembly may vary depending on component fit and the condition of the returned product.

4. RESULTS

Table 4.3: Parameter inputs and assumptions for Scenario 2

Parameter input	Value	Description
Rotor mass	12 kg	Assumption in the simulation
Total rotor gravitational force	117.8 N	Calculated using $F = m \times g$, where $m = 12$ kg and $g = 9.81$ m/s^2 [11]
Force distribution	Equal	Assumption rotor force was equally distributed to both hands-While Pulling
Right hand: Constant force 1	50 N[40]	Force applied by the right hand during the pulling/removal task
Right hand: Constant force 3	58.8 N	Assumed right-hand share of the rotor gravitational force
Left hand: Constant force 2	50 N[40]	Force applied by the left hand during the pulling task
Left hand: Constant force 4	58.8 N	Assumed left-hand share of the rotor gravitational force

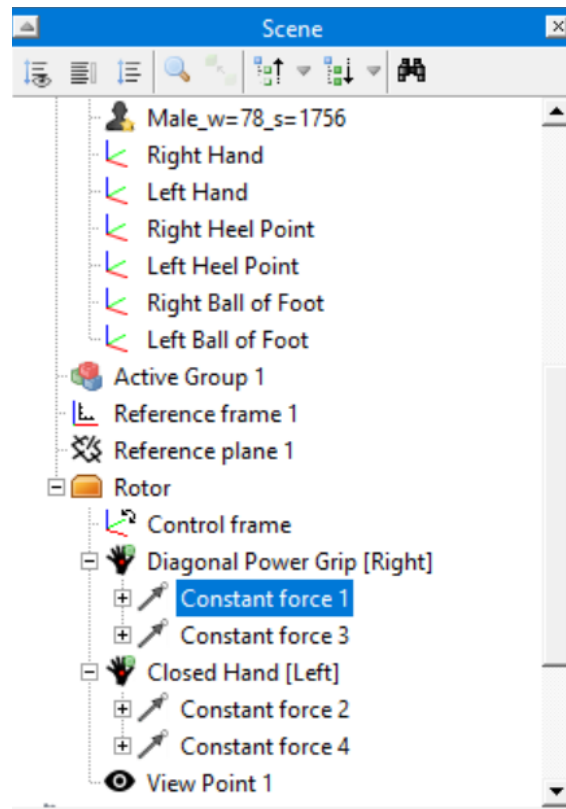


Figure 4.9: Force inputs assigned to Scenario 2

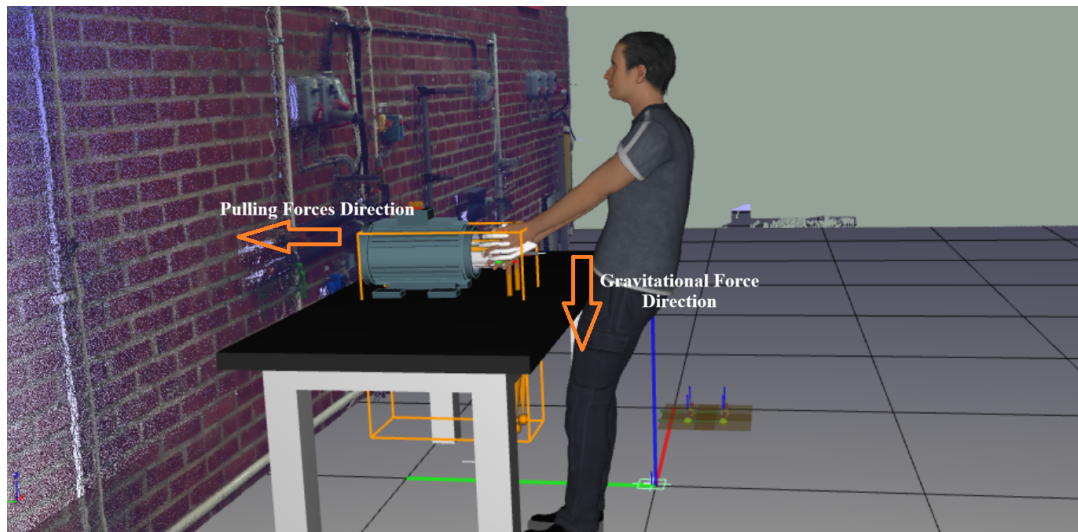


Figure 4.10: Forces in the scenario 2 during the DHM simulation

4.3.2.2 Ergonomic Assessment Result

For scenario 2, REBA was selected to assess the loading result because the rotor pulling task involves whole body posture and manual force exertion. This was characterized by the arm positioning of the worker, his wrist positioning, gripping ability, and the amount of force exerted during the operation. Even though there were small changes in neck, trunk, and legs positioning, it mainly involved the use of both hands to pull while standing.

4. RESULTS

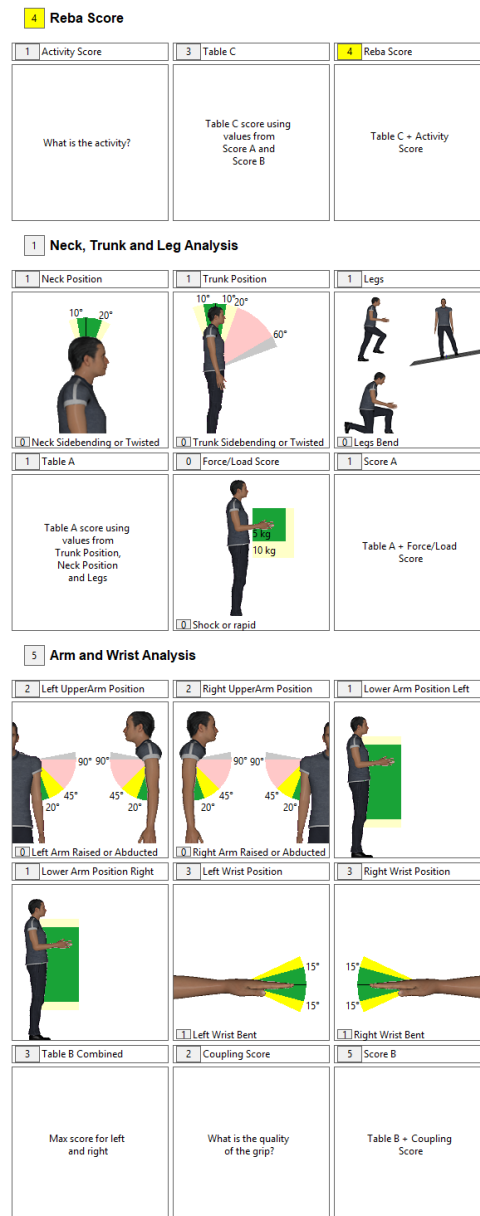


Figure 4.11: Scenario 2 : REBA result from the simulation software.

As shown in Figure 4.11 -the overall REBA score was 4. The score indicated moderate ergonomic risk associated with the task of rotor-stator pulling. Such a score was achieved due to the influence of the posture adopted by the arms of the operator, wrist posture, grip and force exerted. In spite of the relatively neutral posture of the neck, trunk and legs, the pulling activity required the use of both hands.

The REBA analysis indicates that there is no extreme level of hazard for the operation, but it is possible that it might induce ergonomic issues when done frequently or if the resistance to pull increases in actual disassembly. In this case, corrective actions can be applied through better gripping surfaces, a fixture to hold the part steady, proper worktable adjustment, or use of an assisting mechanical pulling mechanism.

The changes would significantly decrease REBA scores for upper arms, wrists, coupling, and force. The new gripping surfaces would help the hands to connect with the rotor and decrease coupling, and the new assisting mechanical device would lessen the input of manual force required by both hands and subsequently lessen the force. The fixture used to hold the component would also eliminate the need for awkward arm and wrist positioning.

4.3.3 Scenario 3

Figure 4.12 illustrates the manikin positioned to push a reinforced, lightweight trolley to transport a heavy machine part, in this case a motor. The manikin holds and supports the trolley with both hands and slightly leans forward to create a balance. This setup was used to evaluate whole-body posture, hand grip, balance, and force application during the transportation task.

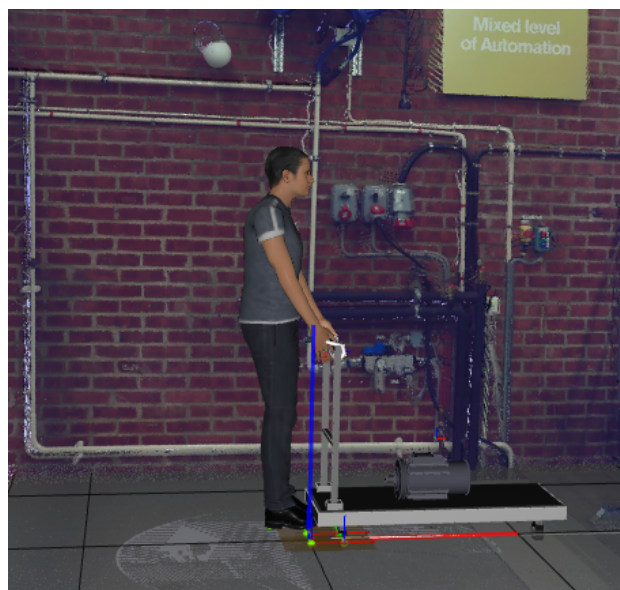


Figure 4.12: Manikin transporting a heavy part using a trolley

4.3.3.1 Scenario description, Assumptions & Calculation

In this scenario, the operator grips both hands on the trolley to push ahead, adding a subsequent force. The force values and assumptions used for Scenario 3 are in Table 4.4 and the Figure 4.14 & Figure 4.13 shows that these forces applied in the scenario. In real conditions, the required pushing force may vary depending on the trolley maneuverability, floor condition and the condition of the handled machine part.

4. RESULTS

Table 4.4: Parameter inputs for Scenario 3

Parameter input	Value	Description
Trolley type	Light-Weight trolley	A lightweight trolley was assumed for transporting the machine part.
Trolley mass	8 kg	Assumption for the trolley -Mass
Machine part mass	25 kg	Assumed mass of the machine part in the trolley.
Total-transported mass	33 kg	Combined mass of the trolley and the machine part.
Total-gravitational force	324 N	Calculated using $F = m \times g$, where $m = 33 \text{ kg}$ and $g = 9.81 \text{ m/s}^2$ [11]
Force distribution	Equal	Assumption-Total force was be equally distributed between both hands while guiding the trolley.
Right hand: Constant force	162 N	Force applied by the right hand while guiding the trolley during transportation.
Left hand: Constant force	162 N	Force applied by the left hand while guiding the trolley during transportation.

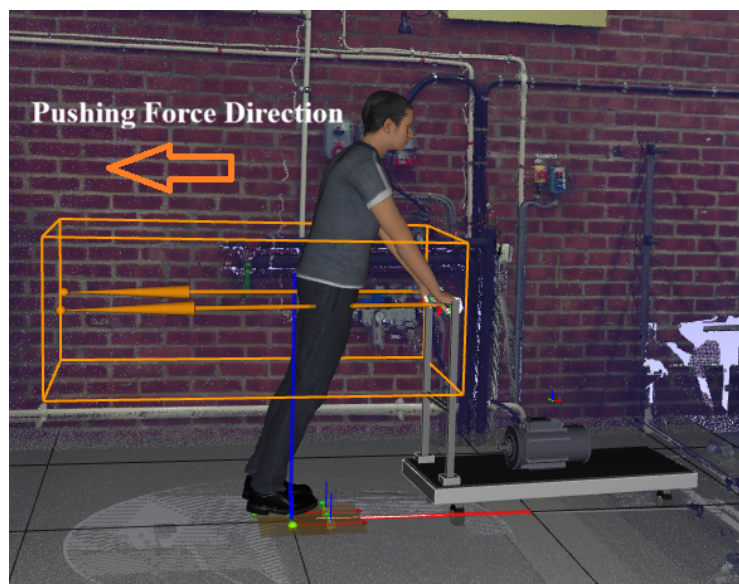


Figure 4.13: Forces in scenario 3 during the DHM simulation

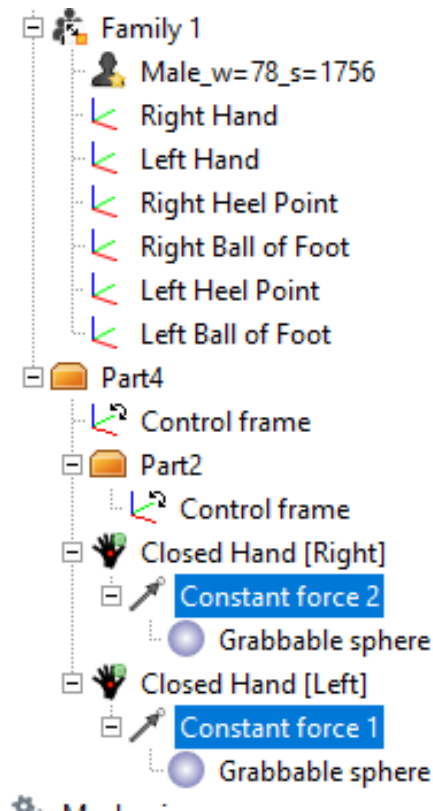


Figure 4.14: Force inputs assigned to Scenario 3

4.3.3.2 Ergonomic Assessment Result

For scenario 3, REBA was chosen since in this case, the task involves whole-body motion with the trunk slightly inclined forward, the hands are in a closed grip but the wrists are extended, and forceful exertion is utilized for moving the trolley and the machine part on top of it.

The task also reflects the body balance condition in correlation with the trunk posture when adding an external force for transporting the load. From the 4.15, the total REBA score is displayed as 4, which accounts for moderate ergonomic risks. The score reflects the whole body postural loading, load, or force coupled with activity conditions.

4. RESULTS

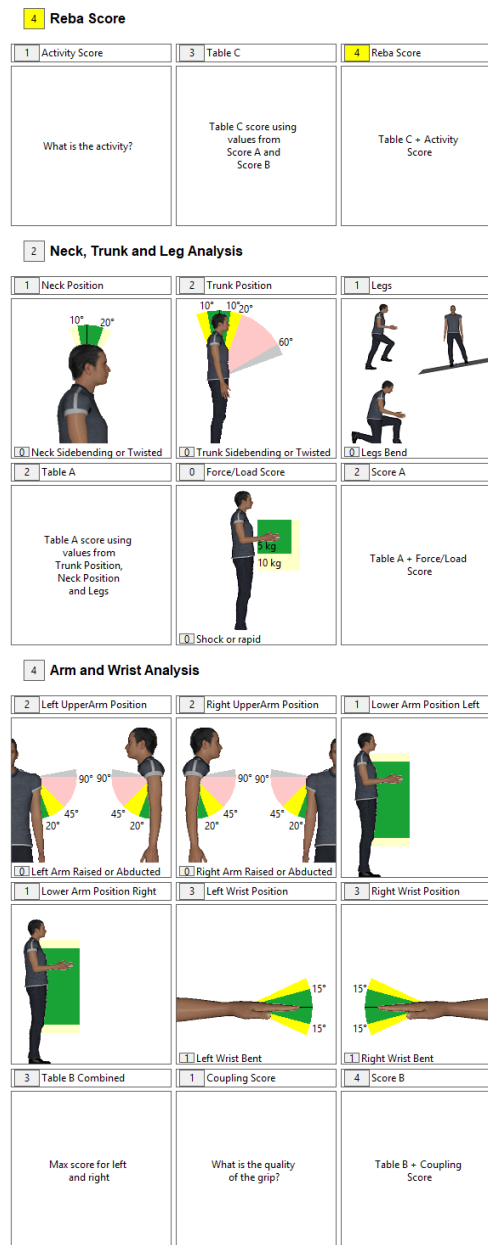


Figure 4.15: Scenario 3: REBA Result from the simulation software.

In real cases, transporting heavy components may occur multiple times in a day, exposing workers to repetitive movements affecting the trunk posture and body balance. Hence, it can be recommended to use hoist cranes and mono rails to transport heavy objects and maintain safety while working on cranes.

The changes would significantly decrease REBA scores associated with the back, arms, and wrists. Utilizing a lifting crane or monorail system would eliminate the requirement for manual pushing and enable the operator to maintain an upright back position. The upper arms and wrists would also work less because the load would not need to be controlled in the same way. Finally, the reduction in the number of times the load is moved manually might mean that the activity score is also reduced.

4.4 Comparing - Simulation Vs KIM Methods

According to the Swedish Work Environment Authority [41], it is recommended to use the ergonomic assessment method KIM to ensure a systematic and standardized evaluation of physical workload [41]. The KIM methods involve different assessment factors to reveal the ergonomic risks from a wider perspective in any workplace environment. The following KIM methods are specifically recommended by the authority.

- KIM-Manual Handling Operation (MHO)
- KIM-Lifting, Holding, Carrying (LHC)
- KIM-Pushing,Pulling (PP) [29]

In the simulation-based interpretation of results, the REBA and RULA assessment methods are implemented in the software to provide an evaluation of postural risks. The RULA method is useful to determine upper-limb postural load in tool-related tasks involving the wrist, arm, shoulders, and neck. In contrast, the REBA method has a greater focus on whole-body loading and includes more assessment factors than RULA. Tasks that primarily feature trunk flexion, leg support, standing positions, load handling, and repetitive actions are suitable to assess with REBA, and these were predominant in the simulation scenarios. The KIM methods are primarily employed to detect ergonomic risks arising from other factors than posture, such as work-environmental conditions, force application, gender differences and time factors, which are not as well covered by RULA and REBA.

Upon assessing the simulation scenarios using REBA, corrective actions were suggested that would affect the partial scores of the method. Still, REBA method does not cover all imaginable factors that could matter for improving ergonomics; hence, a complementary analysis with a method that considers additional factors makes KIM an ideal option.





4.4.1 Scenario 1 - KIM :Manual Handling Operation(MHO)

In scenario 1, we conduct a manual assessment using KIM-MHO, which makes a more abbreviated posture evaluation, but also addresses manual physical workload factors such as force exertion, grip conditions, repetitive actions, duration of exposure, and the surrounding work environment. The KIM-MHO is explicitly designed for manual handling operations and accommodates different levels of force application when using hand tools and assistive devices weighing less than 3 kg. Therefore, it is well-suited to and correctly aligned with the panel removal scenario.

4. RESULTS

KIM for assessing and designing physical workloads during Manual Handling Operations (KIM-MHO)										
Workplace/sub-activity:	SCENARIO 1 : DISASSEMBLY - LOOSENING THE BOLT									
Duration of the working day:	8 hrs	Evaluator:								
Duration of the sub-activity:	2 hrs	Date:	03/06/2026							
1st step: Determination of time rating points										
Total duration of this sub-activity per working day [up to ...]	up to 1	2	3	4	5	6	7	8	9	10
Time rating points:	1	2	3	4	5	6	7	8	9	10
2nd step: Determination of the rating points for other indicators										
Type of force exertion in the finger/hand area within a "standard minute"		Holding ¹⁾			Moving					
		average holding time [sec. per minute]			average movement frequencies [number per minute]					
		31-60	16-30	≤ 15	< 5	5-15	16-30	31-60	61-90 ²⁾	
		Rating points			Rating points					
		5.5	3	1.5	0.5	1	2.5	5	7	
		9	4.5	2.5	0.5	2	4	7.5	11	
		14	7	3.5	1	3	6	12	18	
		22	11	5.5	1.5	5	10	19		
		100	35	8	30			100		
					8	30				
		Rating points of force exertion:		Left hand	Right hand					
				0	30					
Level		Description, typical examples								
low		Very low / low forces (up to 15% $F_{max,M}$) e.g. button actuation / shifting / ordering / material guidance / insertion of small parts								
		Moderate forces (up to 30% $F_{max,M}$) e.g. gripping / joining small work pieces by hand or with small tools								
		High forces (up to 50% $F_{max,M}$) e.g. turning / winding / packaging / grasping / holding or joining parts / pressing in / cutting / working with small powered hand tools								
		Very high forces (up to 80% $F_{max,M}$) e.g. cutting involving major element of force / working with small staple guns / moving or holding parts or tools								
		Peak forces ³⁾ (more than 80% $F_{max,M}$) e.g. tightening, loosening bolts / separating / pressing in								
high		Powerful hitting ³⁾ with ball of the thumb, palm of the hand or fist								
The work cycle must be observed and the rating points for the force categories marked. Added (left and right hands separately), these produce the force rating point. To calculate the total score (step 3), the higher value must be used.										
¹⁾ The amount of time of holding work is only considered as such in the assessment if one arm is held continuously statically for at least 4 seconds!										
²⁾ Please note: If one of these categories was chosen, it is recommended to evaluate this sub-activity also using the KIM-BFI										
³⁾ These forces might not be exerted at all or might no longer be exerted reliably. This applies to women in particular.										
⁴⁾ In case of even higher frequencies, the resulting risk score must be extrapolated linearly or the E version (KIM-MHO-E) must be applied.										
Force transfer / gripping conditions										Rating
Optimum force transfer/application / working objects are easy to grip (e.g. bar-shaped, gripping grooves) / good ergonomic gripping design (grips, buttons, tools)										0
Restricted force transfer/application / greater holding forces required / no shaped grips										2
Force transfer/application considerably hindered / working objects hardly possible to grip (slippery, soft, sharp edges) / no or only unsuitable grips										4
Hand/arm position and movement ⁴⁾										Rating points
Good: position or movements of joints in the middle (relaxed) range, only rare deviations / no continuous static arm posture / hand-arm rest possible as required										0
Restricted: occasional positions or movements of the joints at the limit of the movement ranges / occasional long continuous static arm posture										1
Unfavourable: frequent positions or movements of the joints at the limit of the movement ranges / frequent long continuous static arm posture										2
Poor: constant positions or movements of the joints at the limit of the movement ranges / constant long continuous static arm posture										3
⁴⁾ Typical positions are to be considered. Rare deviations can be ignored.										
Unfavourable working conditions (specify only where applicable)										Rating points
Good: there are no unfavourable working conditions, i.e. reliable recognition of detail / no dazzle / good climatic conditions										0
Restricted: occasionally impaired detail recognition due to dazzle or excessively small details difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise										1
Unfavourable: frequently impaired detail recognition due to dazzle or excessively small details frequently difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise										2
Indicators not mentioned in the table are to be taken into account accordingly.										

Figure 4.16: Scenario 1 KIM -MHO: Page 1[37]

Body posture/movement ^{6) 6)}	Rating points
 <ul style="list-style-type: none"> - Alternation between sitting and standing, alternation between standing and walking, dynamic sitting possible - Trunk inclined forward only very slightly - No twisting and/or lateral inclination of the trunk identifiable - Head posture: variable, head not inclined backward and/or severely inclined forward or constantly moving - No gripping above shoulder height / no gripping at a distance from the body 	0
 <ul style="list-style-type: none"> - Predominantly sitting or standing with occasional walking - Trunk with slight inclination of the body towards the work area - Occasional twisting and/or lateral inclination of the trunk identifiable - Occasional deviations from good "neutral" head posture/movement - Occasional gripping above shoulder height / occasional gripping at a distance from the body 	2
 <ul style="list-style-type: none"> - Exclusively standing or sitting without walking - Trunk clearly inclined forward and/or frequent twisting and/or lateral inclination of the trunk identifiable - Frequent deviations from good "neutral" head posture/movement - Head posture hunched forward for detail recognition / restricted freedom of movement ✓ - Frequent gripping above shoulder height / frequent gripping at a distance from the body 	4
 <ul style="list-style-type: none"> - Trunk severely inclined forward / frequent or long-lasting bending - Work being carried out in a kneeling, squatting, lying position - Constant twisting and/or lateral inclination of the trunk identifiable - Body posture strictly fixed / visual check of action through magnifying glasses or microscopes - Constant deviations from good "neutral" head posture/movement - Constant gripping above shoulder height / constant gripping at a distance from the body 	6 ⁷⁾

⁶⁾ Typical body postures are to be taken into account. Rare deviations can be ignored.
⁶⁾ If the manual handling operations are not carried out in a stationary sitting, standing, kneeling, squatting, lying position, but in motion (walking, crawling), it is recommended to evaluate the sub-activity also using the KIM-BM.
⁷⁾ Please note: If this category was chosen, it is recommended to evaluate this sub-activity also using the KIM-ABP!

Work organisation / temporal distribution	Rating points
Good: frequent variation of the physical workload situation due to other activities (including other types of physical workload) / without a tight sequence of higher physical workloads within one type of physical workload during a single working day.	0
Restricted: rare variation of the physical workload situation due to other activities (including other types of physical workload) / occasional tight sequence of higher physical workloads within one type of physical workload during a single working day. ✓	2
Unfavourable: no/hardly any variation of the physical workload situation due to other activities (including other types of physical workload) / frequent tight sequence of higher physical workloads within one type of physical workload during a single working day with concurrent high load peaks.	4

3rd step: Evaluation and assessment

Type of force exertion in the finger/hand area	+	30			
Force transfer / gripping conditions	+	2			
Hand/arm position and movement	+	2			
Unfavourable working conditions	+	0			
Body posture	+	4			
Work organisation / temporal distribution	+	2			
Time rating points 2 X			Total of indicator rating points:	40	= Result 80

The risk score calculated and the table below can be used as the basis for a rough evaluation:

Risk	Risk range	Intensity of load ⁸⁾	a) Probability of physical overload b) Possible health consequences	Measures
1	< 20 points	low	a) Physical overload is unlikely. b) No health risk is to be expected.	None
2	20 - < 50 points	slightly increased	a) Physical overload is possible for less resilient persons. b) Fatigue, low-grade adaptation problems which can be compensated for during leisure time	For less resilient persons, workplace redesign and other prevention measures may be helpful.
3	50 - < 100 points	substantially increased	a) Physical overload is also possible for normally resilient persons. b) Disorders (pain), possibly including dysfunctions, reversible in most cases, without morphological manifestation	Workplace redesign and other prevention measures should be considered.
4	≥ 100 points	high	a) Physical overload is likely. b) More pronounced disorders and/or dysfunctions, structural damage with pathological significance	Workplace redesign measures are necessary. Other prevention measures should be considered.

⁸⁾ The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an orientation aid. Basically, it must be assumed that the probability of physical overload will increase as the risk scores rise.

Figure 4.17: Scenario 1 KIM-MHO: Page 2 with Evaluation Result

For scenario 1, the KIM-MHO assessment gives a final score of 80, which highlights at the higher end of the second-highest risk range and indicates a substantially increased physical workload. According to the KIM guidance, workplace redesign and other preventive measures should therefore be considered. The high score was mainly influenced by the two-hour task duration, the peak force applied by the right hand, restricted grip conditions, forward leaning, and awkward body posture. This result indicates a more serious workload concern than the REBA score of 5, which classified the task as medium risk and recommended further investigation and changes soon. Possible improvements include using powered tools, improving grip conditions, reducing the required manual force, and limiting the operator's exposure time to the task.

4.4.2 Scenario 2 - KIM:Manual Handling Operation (MHO)

In scenario 2, manual assessment using KIM-MHO is used again due to the matching task situation and physical workload condition. The force exertion and material handling are involved with the task, with strain acting on wrist grip, arms, shoulders, and alteration in body posture by slightly inclining forward for reaching the rotor body while extraction.

From figure 4.16, the KIM-MHO assessment gives a final score of 18, which falls under risk range 1, which means the task has a low physical workload within the simulated conditions. The risk remained low due to both supporting hands and better gripping and equal force distribution on the wrist and arms. Even though the task involved manual pulling and handling, the body posture did not show severe awkwardness, and overall physical work load remains low, and the task can be ergonomically ideal. The scores can get a high risk range if the rotor weights are heavy combined with a lower height for the work table.

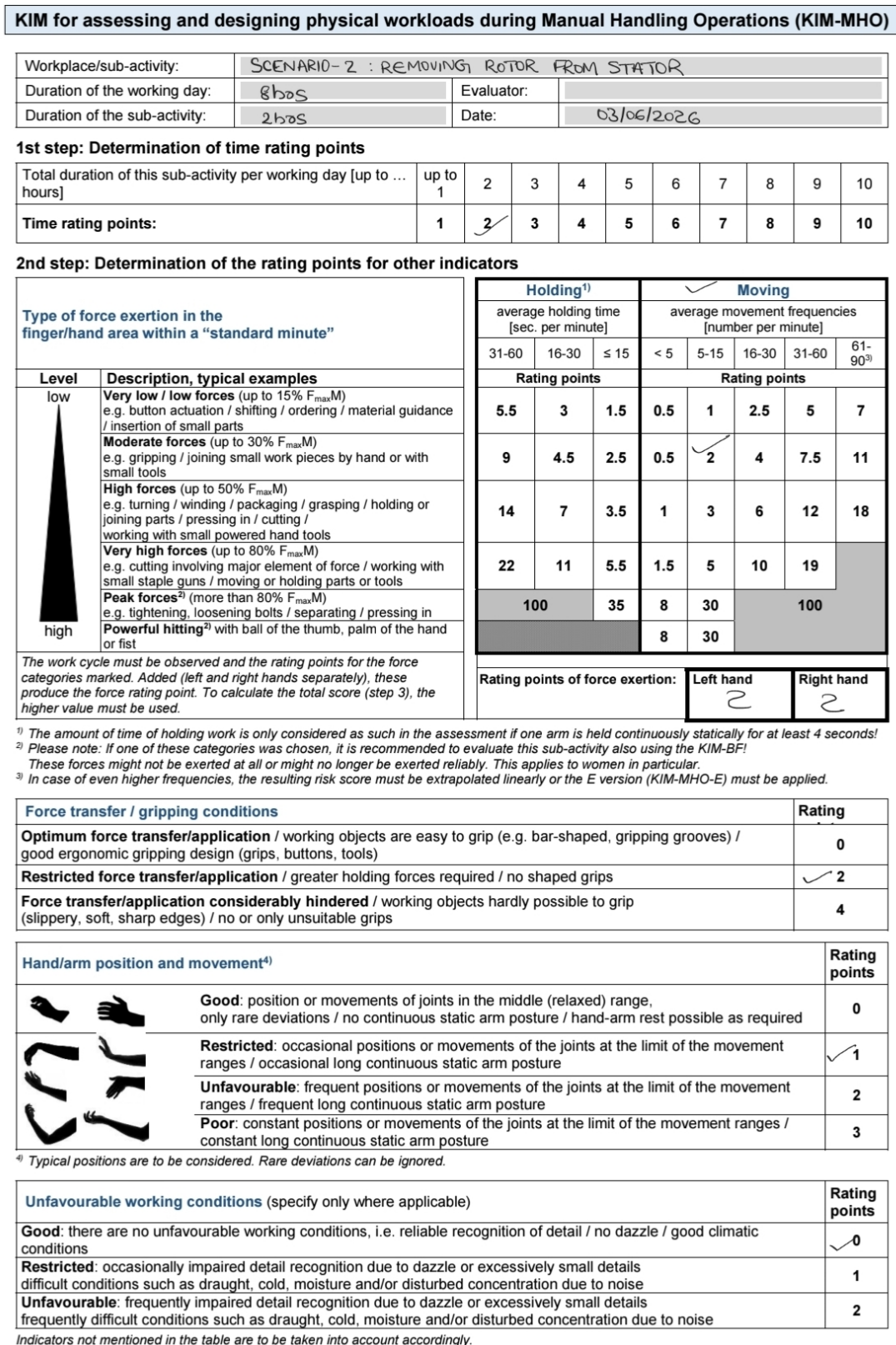






Figure 4.18: Scenario 2 KIM -MHO: Page 1[37]

4. RESULTS

Body posture/movement ^{5) 6)}	Rating points
 <ul style="list-style-type: none"> - Alternation between sitting and standing, alternation between standing and walking, dynamic sitting possible - Trunk inclined forward only very slightly - No twisting and/or lateral inclination of the trunk identifiable - Head posture: variable, head not inclined backward and/or severely inclined forward or constantly moving - No gripping above shoulder height / no gripping at a distance from the body 	0
 <ul style="list-style-type: none"> - Predominantly sitting or standing with occasional walking - Trunk with slight inclination of the body towards the work area - Occasional twisting and/or lateral inclination of the trunk identifiable - Occasional deviations from good "neutral" head posture/movement - Occasional gripping above shoulder height / occasional gripping at a distance from the body 	2 ✓
 <ul style="list-style-type: none"> - Exclusively standing or sitting without walking - Trunk clearly inclined forward and/or frequent twisting and/or lateral inclination of the trunk identifiable - Frequent deviations from good "neutral" head posture/movement - Head posture hunched forward for detail recognition / restricted freedom of movement - Frequent gripping above shoulder height / frequent gripping at a distance from the body 	4
 <ul style="list-style-type: none"> - Trunk severely inclined forward / frequent or long-lasting bending - Work being carried out in a kneeling, squatting, lying position - Constant twisting and/or lateral inclination of the trunk identifiable - Body posture strictly fixed / visual check of action through magnifying glasses or microscopes - Constant deviations from good "neutral" head posture/movement - Constant gripping above shoulder height / constant gripping at a distance from the body 	6 ⁷⁾

⁵⁾ Typical body postures are to be taken into account. Rare deviations can be ignored.

⁶⁾ If the manual handling operations are not carried out in a stationary sitting, standing, kneeling, squatting, lying position, but in motion (walking, crawling), it is recommended to evaluate the sub-activity also using the KIM-BM.

⁷⁾ Please note: If this category was chosen, it is recommended to evaluate this sub-activity also using the KIM-ABP!

Work organisation / temporal distribution	Rating points
Good: frequent variation of the physical workload situation due to other activities (including other types of physical workload) / without a tight sequence of higher physical workloads within one type of physical workload during a single working day.	0
Restricted: rare variation of the physical workload situation due to other activities (including other types of physical workload) / occasional tight sequence of higher physical workloads within one type of physical workload during a single working day.	2 ✓
Unfavourable: no/hardly any variation of the physical workload situation due to other activities (including other types of physical workload) / frequent tight sequence of higher physical workloads within one type of physical workload during a single working day with concurrent high load peaks.	4

3rd step: Evaluation and assessment

Type of force exertion in the finger/hand area	2
Force transfer / gripping conditions +	2
Hand/arm position and movement +	1
Unfavourable working conditions +	0
Body posture +	2
Work organisation / temporal distribution +	2
Time rating points x 2 = Total of indicator rating points:	9 = 18 Result

The risk score calculated and the table below can be used as the basis for a rough evaluation:

Risk	Risk range	Intensity of load ¹⁾	a) Probability of physical overload b) Possible health consequences	Measures
1	< 20 points	low	a) Physical overload is unlikely. b) No health risk is to be expected.	None
2	20 - < 50 points	slightly increased	a) Physical overload is possible for less resilient persons. b) Fatigue, low-grade adaptation problems which can be compensated for during leisure time	For less resilient persons, workplace redesign and other prevention measures may be helpful.
3	50 - < 100 points	substantially increased	a) Physical overload is also possible for normally resilient persons. b) Disorders (pain), possibly including dysfunctions, reversible in most cases, without morphological manifestation	Workplace redesign and other prevention measures should be considered.
4	≥ 100 points	high	a) Physical overload is likely. b) More pronounced disorders and/or dysfunctions, structural damage with pathological significance	Workplace redesign measures are necessary. Other prevention measures should be considered.

¹⁾ The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an orientation aid. Basically, it must be assumed that the probability of physical overload will increase as the risk scores rise.

Figure 4.19: Scenario 2 KIM -MHO: Page 2 with Evaluation Result

From the above figure 4.16, the KIM-MHO assessment gives a final score of 18, which falls under risk range 1, which means the task has a low physical workload within the simulated conditions. The risk remained low due to both supporting hands and better gripping and equal force distribution on the wrist and arms. Even though the task involved manual pulling and handling, the body posture did not show severe awkwardness, and overall physical work load remains low, and the task can be ergonomically ideal. The scores can get a high risk range if the rotor weights are heavy combined with a lower height for the work table.

4.4.3 Scenario 3 - KIM: Pushing, Pulling (PP)

In Scenario 3, Manual assessment using KIM-PP(Push Pull) is used as it is more relevant for the simulative scenario of transporting a heavy machine part in a trolley and moving along a path.

From figure 4.20, the KIM-PP assessment gives a final score of 57, which places the task in a risk range of 3, which means a substantial increase in physical workload. Even though the trolley avoids the physical material handling and lifting, it still allocates a noticeable physical force demand while pushing the trolley ahead with body postures inclining more forward to exert force and movement. The high scores are due to the contribution of weight transportation, body postures, and limited variation in the work action. Overall, the trolley transport task attains a substantially increased risk and is still ergonomically demanding, and needs to undergo corrective actions by using remotely operated overhead hoists to transport heavy parts above the floor and using a lighter trolley with suitable wheels and handles to reduce the force required for transportation.

4. RESULTS




















KIM for assessing and designing physical workloads with respect to manual Pushing and Pulling of loads (KIM-PP)														
Workplace/sub-activity:	SCENARIO 3: TRANSPORTING THE HEAVY PART USING TROLLEY													
Duration of the working day:	8 hrs				Evaluator:									
Duration of the sub-activity:	2 hrs				Date:	03/06/2025								
1st step: Determination of time rating points (distance, duration of the PP)														
Distance ¹⁾ up to ...m ²⁾	40	200	400	800	1200	1800	2500	4200	6300	8400	11000	15000	20000	
Duration ¹⁾ up to ...min ²⁾	≤ 1	≤ 5	≤ 10	≤ 20	≤ 30	≤ 45	≤ 60	≤ 100	≤ 150	≤ 210	≤ 270	≤ 360	≤ 480	
Time rating points	1	1.5	2	2.5	3	3.5	4	5	6	7	8	9	10	
¹⁾ An approximate walking speed of 0.7 m/s (2.5 km/h) when pushing and pulling loads is assumed. ²⁾ Per sub-activity and working day.														
2nd step: Determination of the rating points for other indicators														
Load weight to be moved including transport device [kg]	Transport device									Overhead conveyors	Overhead cranes			
	Barrows ³⁾⁴⁾			Carriages										
				only swivel castors		with fixed castors or lockable swivel castors		pedestrian-controlled						
														
up to 50	3	2	2.5	2.5	3	1	1	1	1	1	1	2		
> 50 up to 100	5	3	4	3	4	1	1	1	1	1	1	2.5		
> 100 up to 200	10	6	7	4	6	2	1.5	1.5	1.5	1.5	1.5	3.5		
> 200 up to 300	50	12	50	5	8	3	2	2	2	2	2	4.5		
> 300 up to 400	100	50	100	7	12	4	3	2.5	2.5	2.5	2.5	6		
> 400 up to 600				12	50	6	5	4	4	10				
> 600 up to 800	100	100	100	50	100	10	8	7	7	7	15			
> 800 up to 1000				15		12	10	10	50					
> 1000 up to 1300	100	100	100	100	100	50	50	50	20	100				
> 1300						100	100	100	50					
³⁾ In addition to the propelling force, the load rating points also consider lifting, tilting, balancing and lowering forces. ⁴⁾ Barrows with support wheels, stair climbing carts and other special designs cannot be differentiated using the KIM-PP. ⁵⁾ E.g. waste containers in outdoor areas with simple wheel bearings, which might be exposed to the weather. Grey fields: These load weights can no longer be moved reliably.														
Driveway conditions						Rating points								
Driveway completely level, smooth, solid, dry, without inclinations														
Driveway mostly smooth and level, with small damaged spots/faults, without inclinations						0	0	0	1					
Mixture of cobbles, concrete, asphalt, slight inclinations ⁶⁾ , dropped kerb						0	1	2						
Mixture of roughly cobbled, hard sand, slight inclinations ⁶⁾ , small edges/sills						1	2	3						
Earth or roughly cobbled driveway, potholes, heavy soiling, slight inclinations, landings, sills						3	5	6						
Additional points in case of significant inclinations or stairs	Inclinations of 2 up to 4° (4 up to 8%)					5	Rating points + additional points Total	0						
	Inclinations of 5 up to 10° (9 up to 18%)					10								
	Stairs ⁷⁾ , inclinations > 10° (18%)					25								
⁶⁾ Slight inclination: up to 2° (4%) ⁷⁾ only for using stair climbing carts														
Unfavourable working conditions (specify only where applicable)						Intermediate rating points IRP			Total IRP (max. 4)					
Regularly significantly increased starting forces, because transport devices sink into the ground or get wedged						3			0					
Frequent stops with braking / without braking						3 / 1								
Many changes of direction or curves, frequent manoeuvring						3								
Load must be positioned precisely and stopped, driveway must be adhered to precisely						1								
Increased movement speed (approx. 1.0 up to 1.3 m/s)						2								
None: there are no unfavourable working conditions						0								

Figure 4.20: Scenario 3 KIM-PP: Page 1[38]

Unfavourable properties of the transport device/overhead conveyor/overhead crane	Intermediate rating points IRP	Total IRP (max. 4)
No suitable handles or construction parts for applying force	2	0
No brake when driving on inclinations > 2° (> 3%)	3	
Unadjusted castors (e.g. too small on soft or uneven floor)	2	
Defective castors (worn-out, rubbing, stiff, air pressure too low)	2	
None: there are no unfavourable properties of the transport devices	0	

Body posture / body movement ⁸⁾	Rating points
 <ul style="list-style-type: none"> Trunk upright or slightly inclined forward, no twisting Force application height can be selected freely No hindrance for the legs 	3
 <ul style="list-style-type: none"> Body inclined towards the direction of movement or slight twisting when pulling the load on one side Fixed force application height ranging from 0.9 – 1.2 m No or only slight hindrance for the legs Predominantly pulling 	5
 <ul style="list-style-type: none"> Awkward body postures caused by <ul style="list-style-type: none"> Fixed force application height < 0.9 or > 1.2 m Lateral force application on one side Significantly obstructed view Significant hindrance for the legs Frequent/constant twisting and/or lateral inclination of the trunk identifiable 	8

⁸⁾ The typical body posture is to be taken into account. If the trunk is inclined to a greater extent when starting, braking and manoeuvring, this is taken into account under unfavourable working conditions.


Work organisation / temporal distribution	Rating points
Good: frequent variation of the physical workload situation due to other activities (including other types of physical workload) / without a tight sequence of higher physical workloads within one type of physical workload during a single working day.	0
Restricted: rare variation of the physical workload situation due to other activities (including other types of physical workload) / occasional tight sequence of higher physical workloads within one type of physical workload during a single working day. RESTRICTED VARIATION ASSUMED	2
Unfavourable: no/hardly any variation of the physical workload situation due to other activities (including other types of physical workload) / frequent tight sequence of higher physical workloads within one type of physical workload during a single working day with concurrent high load peaks.	4

3rd step: Evaluation and assessment

Load weight / transport device	2.5				
Driveway conditions +	0				
Unfavourable working conditions (Σ IRP) +	0				
Properties of transport device (Σ IRP) +	0				
Body posture +	5				
Work organisation / temporal distribution +	2				
Time rating points x 6		= 9.5			
		Total of indicator rating points:			
		Pushing and Pulling in pairs: x 0.7			
			x 1.3		
				= 5.7	Result

In case of female employees: → CONSIDERING MALE EMPLOYEE

The risk score calculated and the table below can be used as the basis for a rough evaluation:

Risk	Risk range	Intensity of load	a) Probability of physical overload b) Possible health consequences	Measures	
	1	< 20 points	low	a) Physical overload is unlikely. b) No health risk is to be expected.	None
	2	20 - < 50 points	slightly increased	a) Physical overload is possible for less resilient persons. b) Fatigue, low-grade adaptation problems which can be compensated for during leisure time	For less resilient persons, workplace redesign and other prevention measures may be helpful.
	3	50 - < 100 points	substantially increased	a) Physical overload is also possible for normally resilient persons. b) Disorders (pain), possibly including dysfunctions, reversible in most cases, without morphological manifestation	Workplace redesign and other prevention measures should be considered.
	4	≥ 100 points	high	a) Physical overload is likely. b) More pronounced disorders and/or dysfunctions, structural damage with pathological significance	Workplace redesign measures are necessary. Other prevention measures should be considered.

⁹⁾ The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an orientation aid. Basically, it must be assumed that the probability of physical overload will increase as the risk scores rise.

Figure 4.21: Scenario 3 KIM-PP: Page 2 with Evaluation Result

5

DISCUSSION

In the following chapter, the main findings of the study are discussed.

5.1 Ergonomic Risks In Remanufacturing Work

The study's findings address the first research question, identifying which remanufacturing work phase carries the greatest ergonomic risks and specifying the types of risks involved. Among the evaluated phases, the disassembly stage exhibits the highest level of ergonomic risk in the chosen remanufacturing workstation. According to the interview results, remanufacturing involves highly labor-intensive tasks with complex work patterns, which generate unpredictable ergonomic risks and extend the duration of repetitive activities and physical strain required to meet the objective of returning the product within the designated time frame. The simulation study was subsequently employed to analyze the ergonomic risks associated with this selected phase in greater depth.

The disassembly work stage consists of activities and tasks undergoing high to moderate ergonomic risks due to the higher complexity in the workflow. There are situations in which the operator's physical workload exceeds what is normal while dismantling any seized or corroded machine part, which requires extra manual effort and physical strain, which may involve repetitive actions with physical forces, strains, and wide alterations in the physical body posture, awkwardness, and affected body balance. As a result of complexity and increased lead time of work, operators' physical and mental stress builds up to cope with the target objectives, which could lead to the bypassing of safety protocols and an increase in near-miss incidents and accidents.

The main ergonomic risks observed in the study were awkward postures, forceful exertion, upper body physical strains at the wrist, arms, and shoulders, along with whole body postures, trunk activity, repetitive work, prolonged time occurrence, material handling of heavy object parts, and poor accessibility. These risks were correctly aligned with the disassembly tasks within the remanufacturing workstation. The overview of interview findings also emphasized that other work phases have more serious ergonomic problems, such as cleaning and assembling all of which are time-consuming and involve physical overloads for the laborers in the process and product conditioning. However, these processes tend to follow more standardized approaches and have safer operating procedures, whereas disassembly involves deformed and deteriorated components and parts, requiring significant physical involvement and posing a higher risk.

The simulation analysis further strengthened the qualitative findings. While evaluating the results of three simulation scenarios with REBA and KIM methods, there is a combination of ergonomic risks observed based on force, manual material handling, body posture and balance, repetition, accessibility, and task duration. The disassembly work phase is identified with maximum ergonomic risks, and the prominent risks are forceful exertion, awkward body postures, upper body inclinations, trunk activity, manual handling, working with physical overload conditions, repetitions, unsuitable working heights, and less accessibility.

5.2 Interpretation of Ergonomic Results

In the research, the second research question focuses on which ergonomic assessment method can be applied to identify high-risk activities in remanufacturing workstations. Using a single assessment method is not sufficient to understand or identify the ergonomic risks in the selected disassembly workstation. So the combination of the posture-based assessment and workload-based assessment gives a clearer understanding of the physical demands involved in remanufacturing tasks.

The simulation-based assessment primarily has RULA and REBA built into the software for the assessment of the manikin during three scenarios. Since the tasks involved full-body movements, trunk positions, arm and wrist placements, grip situations, and force application, the REBA was ideally preferred for evaluation because the disassembly tasks were not just about moving upper limbs; operators had to lean, reach, stand, pull, and maintain their posture while applying force. Therefore, REBA was chosen over RULA for interpreting these simulations. Still, RULA could be helpful for tasks focused solely on upper-limb positions, like detailed hand-tool work.

The REBA results showed a moderate ergonomic risk level in the three scenarios.

- Scenario 1 : REBA score of 5
- Scenario 2 : REBA score of 4
- Scenario 3 : REBA score of 4

This indicates that none of the simulated scenarios showed an extreme ergonomic risk under the assumed conditions, but all tasks still require attention if they are performed repeatedly or for a long duration. Scenario 1 showed the highest REBA score because bolt loosening required manual force, forward leaning, arm elevation, wrist involvement, and grip effort. This means that even a common task such as removing bolts can become ergonomically demanding when it includes awkward posture, restricted access, and repeated tool use.

Although REBA includes force/load as part of the assessment, it mainly focuses on body posture and gives only a simplified consideration of physical workload. Therefore, REBA alone was not sufficient to fully explain factors such as task duration, repetition, transportation conditions, and pushing or pulling demands. As Scenario 2 and 3 both got the same REBA score. Still, both have different activities- in Scenario 2, operator was pulling a rotor and in the scenario 3, operator was moving a heavy part with a trolley. So, while REBA does well at spotting postural risks, it

clearly needs a different approach to properly cover manual tasks, repetitive forceful actions, and push-pull duties.

KIM was useful for this purpose because it evaluates physical workload in relation to the specific type of task. KIM-MHO was applied to Scenarios 1 and 2 because these tasks involved manual handling, force exertion, gripping, and hand-arm activity. KIM-PP was applied to Scenario 3 because the task involved pushing and pulling a trolley. This helped to complement the ergonomic risks from a perspective other than posture alone. Section 3.6 also explains that KIM can be included to assess manual handling tasks such as lifting, carrying, pushing, pulling, and repetitive manual handling, while REBA and RULA can be used mainly for posture-based evaluation in the digital simulation.

The KIM results showed differences; Scenario 1 received a KIM-MHO score of 80, indicating an increased physical workload. This higher score was mainly influenced by peak force, forward leaning, and awkward posture. This result shows that the bolt-removal task is not only a posture-related issue but also a workload issue, especially when it is repeated over time.

In Scenario 2, the KIM-MHO score was 18, putting it in a lower risk range for the simulated situation. This score makes sense due to the use of both hands, an even force distribution, and a better body posture while pulling. But just because the risk seems low here doesn't guarantee safety in real scenarios. Risks go up if the rotor is heavier, or the part is stuck. So, one needs to be careful when interpreting these results since they're heavily dependent on the simulation's assumptions.

Scenario 3 had a KIM-PP score of 57, showing an increase in physical workload during trolley transport. Though the trolley cuts down on direct lifting, it doesn't eliminate all risks. Pushing, pulling, gripping, and repetitive motions are still part of it. So, while this equipment makes some tasks easier, it introduces other challenges. The findings show that using a trolley reduces one kind of risk but creates the physical effort in different ways.

This leads us to think that using different methods is key when looking at ergonomics in remanufacturing. By combining approaches, we get a good grasp of both obvious posture issues and less noticeable workload problems.

5.3 Suitability of Digital Simulation for Ergonomic Analysis

Based on the study's results, digital simulation proves to be an effective approach for assessing ergonomic risks in remanufacturing workstations. A successful interaction and coordination with IPS-IMMA helped in creating a digital version of selected manual disassembly scenarios, learning the scope of innovation in digitalized er-

gonomic prospects, and exploring how well it can be implemented for future aspects. Working with the simulation software allowed us to create and manipulate workplace scenarios with operators' body postures, movements, and force applications, and to add special constraints and effects for realistic rendering and simulation. The tools, machine parts, equipment, and other background accessories were designed using the CATIA V5 software within the correct scale, representing the operator's physical conditions and tolerance. By using a digital manikin, the work can be designed and planned in a controlled environment, and the possible ergonomic risks and solutions can be identified before implementing changes into real-world scenarios.

Usually, in remanufacturing facilities, returned products have different characteristics based on wear, corrosion, damage, and contamination, and the work pattern becomes unpredictable with more variations. Hence, the operator may be unable to follow a standardized working procedure, which leads to extra physical strain, force exertion, and overload due to bending and awkward postures, totally depending upon the product and time limit aspects. The digital simulation version helps to identify these unpredictable situations and showcases the moderate to extreme conditions in which these tasks affect the operator's health and safety.

In this thesis, we choose the theoretically simplest sequence of randomized tasks associated with the disassembly work phase, categorized as scenario 1, scenario 2, and scenario 3. Creating a simulation sequence for these work tasks provides a final evaluation using REBA assessments. As the chosen scenarios primarily involved whole-body risk exposures—such as inclination, trunk movement, wrist and arm loading with force exertion, leg activity during bolt removal, changes in posture, material handling during rotor removal, and finally body balance, posture, and hand force during the transportation task—the digital ergonomic simulation makes these risks more transparent and easier to identify.

5.3.1 Practical Challenges in Project Execution

During the course of the project, difficulties arose in obtaining access to empirical data for the quantitative phase, particularly in securing detailed visual observations and analyses of working conditions at the targeted stations, which limited the possibility of expanding the study's overall scope. The scenarios were therefore mainly developed from semi-structured interviews, follow-up discussions with industry experts, available product information, and calculated or assumed values. This made it possible to create realistic task examples, but some factors, such as the actual force required to remove damaged components, task duration, repetition, and differences between operators, could not be measured directly.

Another challenge was representing the variability that is common in remanufacturing. Returned products can differ considerably in their condition, which means that the same task may require different levels of force, different postures, or different tools. A single simulation scenario cannot represent all of these possible conditions.

5.4 Implications for Workstation Improvement

The results from the simulation-based analysis and the KIM assessment indicate that ergonomic enhancements at the workstation should prioritize: reducing excessive manual force, optimizing working posture, improving accessibility, and facilitating the handling of heavy components.

In scenario 1, manual bolt removal should place less strain on the wrist, avoid awkward leaning positions, and reduce repetitive force. These improvements can be achieved by using power tools instead of manual tools, improving grip ergonomics, elevating work surfaces, and minimizing time-consuming bolt-loosening tasks.

For scenario 2, the component extraction task indicated a lower risk level based on the simulation assumptions; however, under real operating conditions, the situation may be more complex and physically demanding. The setup should provide more support for components that must be separated. Using fixtures, clamps, improved gripping surfaces, and simple mechanical aids can reduce strain on the wrists, arms, shoulders, and back.

In scenario 3, using a trolley for transporting heavy components reduces the amount of direct lifting, though it does not fully remove the physical workload. Therefore, in addition to optimizing the trolley design and ensuring that the wheels roll smoothly, it is important to consider shorter transport distances and better floor conditions. Introducing mechanical aids such as hoists or monorails for heavier items can further decrease the need for repeated manual pushing and pulling.

The workstation should enable operators to work with less exertion, improved posture, and safer movement patterns. Adjustable worktables and tools, combined with stable fixtures and mechanical assistance can help to reduce ergonomic risks. This also contributes to making remanufacturing tasks significantly safer.

5.5 Summary

This study indicates that ergonomic risks in remanufacturing are largely linked to its labor-intensive nature and the variability of tasks. Disassembly emerges as the most physically demanding stage because it involves manual tool handling, the exertion of force, awkward working postures, difficult-to-access components, and frequent manual handling of parts.

Through the simulation-based REBA assessment, posture-related hazards were identified. In parallel, the KIM assessment highlighted additional aspects, considering factors such as force exertion, repetitive movements, task duration, and push-pull operations. A comparison of the two methods shows that their combined use is more effective than relying on either one in isolation.

The discussion shows that making ergonomic improvements is justified. These

should reduce excess manual force and improve posture and accessibility. We also need to support better component handling and lessen repetitive physical tasks. Overall, the findings support using digital simulation along with other ergonomic methods. This helps to spot and improve risky activities in remanufacturing workstations.

5.6 Limitations

This thesis has some limitations that should be considered when interpreting the findings.

- The study examined only a specific remanufacturing workstation at disassembly stage, and therefore does not capture all remanufacturing processes or workstation types.
- The simulation scenarios were created using expert interviews, available product data, and several assumptions.
- There was no direct observation of actual operators performing the exact tasks, meaning the simulation reflects a simplified representation of reality.
- The forces, weights, working postures, and task durations used in the simulation were derived from assumptions and existing reference data. In practice, these parameters may vary depending on the condition of the returned product.
- The suggested ergonomic improvement measures were not physically implemented or evaluated in an actual workstation. Consequently, their real-world impact on lowering ergonomic risk, fatigue, or work-related musculoskeletal strain could not be confirmed within the scope of this thesis.

5.7 Future Work Recommendations

In future research, operators should be observed directly at real remanufacturing workstations. This would enable the collection of detailed data on posture, body movements, task duration, repetition rates, exerted forces, and the actual conditions at the workstation.

A broader range of remanufacturing workstations should be included, such as cleaning, inspection, reprocessing, and assembly. Although disassembly emerged as the most ergonomically demanding phase in this study, other stages can also present substantial ergonomic risks depending on the specific product and process characteristics.

The outcomes of the digital simulations should be verified against real-world data from the workplace, including video analysis, operator feedback, and force measurements. Such validation increases the credibility of the simulations and ensures that ergonomic evaluations more closely reflect real working conditions.

Subsequent steps should emphasize testing the proposed interventions in practice. This could involve evaluating powered tools, height-adjustable worktables, and other assistive devices to determine their impact on reducing ergonomic risk.

Finally, companies involved need to integrate digital human modeling with scoring approaches such as REBA and KIM; high-risk tasks can be identified in advance, helping to prevent worker fatigue, discomfort, reduced work quality, and musculoskeletal disorders.

6

CONCLUSION

Our thesis study aimed to analyse and evaluate ergonomic risks in a labour-intensive remanufacturing work station using digital human simulation and ergonomic assessment methods. The study combined the findings from the literature, semi-structured interviews with industrial and academic experts, and a simulation-based analysis of selected manual disassembly tasks.

The first research question focused on identifying which work phase was most exposed to ergonomic risk and what types of risks were present. The findings show that disassembly was one of the most ergonomically demanding phases in the selected remanufacturing context. The literature review, interview results, and simulation analysis all corroborated the identified conditions and factors. Across these findings, it was highlighted how strongly remanufacturing operations rely on manual labour and the necessity to cope with high product variability. The labour-intensive handling of returned products leads to more complex work routines and unpredictable operating procedures, caused by wear, degradation, and seizure of product components. As a result, operators must constantly adjust to changing conditions, modifying their body postures, applying additional physical force, and selecting different tools for each specific task. This is particularly evident when working in confined spaces, dismantling machine subassemblies, and exerting extra effort to properly extract components with special tools—activities that require more time and repetition and lead to heightened physical and mental strain within a restricted work environment.

The second research question focused on which ergonomic assessment methods could be used to identify high-risk activities. The study found that the most suitable method depends on the type of task which was being assessed. REBA was selected as the primary assessment method in the IPS-IMMA simulation because the scenarios involved the whole body, including the trunk, arms, wrists, standing posture, balance, grip, and force application. The REBA results showed moderate ergonomic risk in all three scenarios, with bolt removal receiving the highest score. The study suggests that REBA alone was not enough to fully describe the physical workload of the tasks. Factors such as frequency and time duration, repetition, manual handling conditions, and pushing or pulling demands were not captured in the same level of detail. For this reason, KIM was applied separately as a complementary method. KIM-MHO was used for the bolt-removal and rotor-extraction tasks, while KIM-PP was used for the trolley-transportation task. KIM method was manually deployed, finding it a more ideal option. The results from REBA and KIM give different scores for each task with a complementary perspective. When REBA added insights on the body posture-related risk, KIM provided a clear idea of physical load and constraints

aligned to the tasks.

The third research question focused on the suitability of digital simulation for ergonomic analysis in remanufacturing. The study found that digital human simulation is a useful tool for identifying and analysing possible ergonomic risks, especially during the early stages of workstation assessment and improvement. IPS-IMMA software made it possible to model operator postures, degree-of-freedom movements, reach conditions, force application, and task sequences in a controlled digital environment. This highlights the opportunity to examine and assess the tasks, identify better solutions and corrective measures, and only then apply them in real-world implementation.

In this thesis, the simulation scenarios were developed from expert interview sessions, product information, and standard measurements based on classification societies, force calculations, and assumptions related to component weight, task duration, working posture, and workplace conditions. Therefore, the results should be understood as indicators of possible ergonomic risks rather than exact measurements of real workplace exposure.

The findings indicate that ergonomic improvements should focus on reducing excessive manual force, improving working height, body postures, and accessibility, using suitable tools and fixtures, reducing repetitive exposure, and introducing mechanical assistance when handling or transporting the heavy components. The digital simulation can provide valuable support for ergonomic assessment in remanufacturing when it is combined with appropriate assessment methods and practical expert knowledge. This approach can help identify high-risk activities earlier and support the development of safer and more human-centred remanufacturing workstations.

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Appendix A: Interview Guide

Since the interviews were semi-structured in the research type, the authors have altered a few questions and asked several follow-up questions. However, the nature of questions has remained the same. The interview questions were developed and refined to allow participants to answer in line with their specific professional responsibilities and their engagement in remanufacturing activities. This strategy made it possible to gather perspectives from individuals involved in various stages of the remanufacturing.

The interview responses were thoroughly examined and synthesized in the Results section of this report. In certain instances, minor language edits were applied to enhance clarity and readability, and the intentions of the interviewees were consistently maintained throughout the analysis.

Question addressed to the Industrial Professionals in Remanufacturing

- What is your current role within the remanufacturing process? How long have you been working in this position?
- Which specific work phases are you primarily involved in (e.g., inspection, disassembly, cleaning, reconditioning, assembly)?
- Can you describe the tasks you perform during a typical shift for remanufacturing?
- Which tasks are the most time-consuming and the most physically demanding?
- During which work phase have the greatest physical strain? or experience discomfort, fatigue, or pain related to specific tasks?
- How are work-related ergonomic risks currently identified or reported?
- Have any ergonomic assessments previously been conducted at this workstation?
- Are you aware of any formal ergonomic evaluation tools being used? Or does your company use any specific?
- Which tasks would require a detailed ergonomic evaluation to be taken seriously?
- Do you believe improvements in workstation design could reduce physical strain? If yes, how?
- How might improved ergonomics affect productivity, workflow stability, or quality performance?
- In your opinion, how should worker safety and production efficiency be effectively balanced?

Question addressed to the Academic Experts in Remanufacturing and Manufacturing

- Could you briefly describe your research focus in remanufacturing systems, and your current role in the industry, which is related to remanufacturing?
- How long have you been in the field of remanufacturing or circular manufacturing systems?
- From your observations or collaborations, what types of manual tasks are commonly involved in remanufacturing operations?
- From your experience working with remanufacturing systems, which work phases tend to expose operators to the highest physical workload or strain?
- What operational challenges do companies face when managing remanufacturing processes?
- When operators perform remanufacturing tasks, what kinds of physical challenges do they usually experience—for example, awkward postures, repetitive movements, lifting heavy components?
- In your opinion, what key factors should researchers consider when analysing working conditions in remanufacturing operations?
- In real industrial settings, how do production deadlines or productivity targets influence how operators perform remanufacturing tasks?
- In your opinion, do human factors—such as operator skills, and ergonomics—play an important role in making remanufacturing systems sustainable in the long term?
- One common challenge in remanufacturing is the variability of returned products. Does the variability influence the way operators perform tasks ?
- From your research perspective, what areas related to human factors or workforce conditions in remanufacturing still require further research?
- Is there any advice you would give to researchers studying labour-intensive remanufacturing environments?

Question addressed to the Ergonomist

- Could you briefly describe your role and responsibilities related to ergonomic risk evaluation in remanufacturing environments?
- How long have you been working with ergonomic assessment in industrial systems?
- To what extent are you involved in workstation design or improvement activities across manufacturing or remanufacturing operations?
- Based on your experience, which types of tasks in remanufacturing operations typically present the highest ergonomic risks?
- What physical risk factors (for example, awkward postures, repetitive movements) are most commonly observed in labour-intensive remanufacturing workstations?
- Are there differences in ergonomic risk exposure between manufacturing and remanufacturing processes? If yes, how would you describe them?
- How do workstation layout, component accessibility, and tool positioning influence operator posture and movement patterns in remanufacturing environments?

- Which environmental conditions most influence ergonomic exposure in such operations?
- How do you decide which assessment method (eg, RULA, REBA) is most appropriate for analysing specific manufacturing or remanufacturing tasks?
- How are ergonomic risks usually identified, documented, and communicated within remanufacturing organizations?
- At what stage of workstation design, redesign, or process improvement should ergonomic assessment ideally be introduced?
- how do ergonomic improvements influence worker safety and long-term health outcomes in remanufacturing environments?
- How can ergonomic improvements affect productivity or quality performance in labour-intensive remanufacturing systems?
- In your experience, can ergonomic interventions help reduce errors, rework, or process delays in remanufacturing operations?
- What types of workstation redesign strategies are usually most effective in reducing operator strain in environments?
- Is there any additional recommendation you would suggest when selecting a workstation for ergonomic risk evaluation in remanufacturing studies like ours?