



Multi-criteria assessment methodology for remanufacturing conventional grinding machines into CNC machine tools

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Abstract: *Purpose:* This paper presents a multi-criteria assessment methodology to evaluate the remanufacturability of converting conventional surface grinding machines into CNC machine tools.

Methodology: Conventional surface grinding machines remanufactured into CNC machine tools were analyzed and classified into five remanufacturing alternatives. A multi-criteria assessment model incorporating cost, time, accuracy, reliability, processing shape complexity, and ergonomics was developed. The importance of criteria and performance of alternatives were weighted through machine tool remanufacturing experience analysis and comparative literature review.

Results: The Remanufacturability Index (RI) for remanufactured conventional surface grinding machines ranges from 0.637 to 0.999 based on the level of CNC upgrades from 2-axis to 5-axis configurations. Higher-axis remanufactured machines showed greater feasibility.

Theoretical Contribution: This study provides a quantitative methodology to assess the technical, economic, and environmental feasibility of remanufacturing conventional machines into CNC machine tools. It extends the application of multi-criteria decision making to the field of machine tool remanufacturing.

Practical Implications: The proposed methodology can guide small and medium-sized manufacturers in making decisions to upgrade their conventional



machines to CNC through remanufacturing. It helps evaluate the benefits and risks of different upgrade configurations to support the implementation of machine tool remanufacturing in practice.

Keywords: conventional surface grinding machine tool remanufacturing, conventional surface grinding into CNC machine tool remanufacturing, integrated remanufacturing-upgrading, remanufacturability assessment, multi-criteria remanufacturing assessment

Sustainable Development Goals (SDGs): **SDG 9:** Industry, Innovation and Infrastructure; **SDG 12:** Responsible Consumption and Production; **SDG 8:** Decent Work and Economic Growth; **SDG 13:** Climate Action; **SDG 4:** Quality Education

1. Introduction

High-value-added waste mechanical and electrical products based on high-tech maintenance to satisfy industrialization development is called remanufacturing. Remanufacturing supports the industry's transformation from an extensive to an intensive resource recycling approach. Green, intelligent, supernormal, integrated, and service mechanical engineering technology trends represent the key, which is the core link of the discipline system of remanufacturing engineering. Remanufacturing engineering and technology are deeply integrated with the development of digitalization, informatization, and intelligence and promote the transformation from quality manufacturing to Intelligent manufacturing (Zhu et al., 2023).

Remanufacturing is highly industry-dependent and much more complex than traditional manufacturing to be of well-known benefits as a value recovery strategy for end-of-life products, so remanufacturing requires the implementation of digital technologies to overcome the complexity and time limits to conduct successful large-scale implementation of remanufacturing activities. Remanufacturing should contribute to the circular economy by scaling remanufacturing activities in mature, complex industries that produce highly polluting waste (Franzè et al., 2023).

The reflected uncertainty in market demand is due to the open-loop product lifecycle that includes product design, production, sale, service, and end-of-life strategy. A more complex supply chain structure and more significant uncertainty in supply chain decisions arise by extending remanufacturing to the product lifecycle. The product life cycle is changed from an open-loop to a closed-loop by introducing collecting and remanufacturing to the supply chain at the end of a product's service life. Thus, the market demand uncertainty includes the quantity and quality of the used product, the time of collecting, and the uncertainty of the remanufacturing process's disassembly, cleaning, and inspection activities (Li et al., 2023).

The remanufacturing industry grew by 15% between 2009 and 2011 to reach US\$43 billion and provide 180,000 jobs in 2011 in the US. Remanufacturing and other value recovery operations created C\$44 billion in total revenues and provided 375,000 direct jobs in 2019 in Canada. Remanufacturing can create a new profit stream but cannibalize the demand for new products, resulting in a loss of profit. Innovative new products due to the improved profit margin with the value-adding innovative features are highly affected by the cannibalization effect of remanufacturing, so the advantages and disadvantages of remanufacturing should be carefully assessed in an innovative industry (Cetin & Zaccour, 2023).

Machinery remanufacturing is energy-consuming and susceptible to quality uncertainty of used products, which increases the variability of cost and carbon emission and affects the production decisions of the original equipment manufacturer in return. The optimal remanufacturing mode and strategy assessment of machinery should be conducted according to the quantity of new and remanufactured products, profits, and carbon emissions. Remanufacturing models with the constraints of quality uncertainty of end-of-life machines that include the total amount of used products to be collected and remanufactured, the cost and carbon emissions in the remanufacturing process are regarded as uncertain as various quality levels of used machines are of different cost and carbon emissions of the remanufactured product and quality uncertainty (Qin et al., 2023).

The ability to integrate the educational institutions to conduct the remanufacturing of machine tools as a business was assessed to develop the manufacturing-remanufacturing strategy of

conventional into CNC machine tools. Energy consumption and CO₂ emissions criteria can be developed to help conclude feedback about environmental benefits. The remanufacturing process usually contains activities of disassembly, sorting, cleaning, processing, upgrading, and reassembly, and to add more flexibility, the magnetic fixture was developed to enable the mechanical interface, linear ball rails-carriages slides, and ball lead screws were reassembled to conventional vertical turret milling machine tool. The hybrid labor-student remanufacturing environment can be specific by adopting cheap CNC technology and capabilities of educational institutions to deliver hybrid public-private services that were aimed at establishing triple-bottom sustainability of economic, environmental, and social pillars (Abdullah, Sheng & Yun, 2018).

Conventional lathe machine tool remanufacturing to produce CNC machine tools was subjected to a multi-alternatives-based sustainability modeling process. Remanufacturing is subjected to an agile portfolio to eliminate gearboxes, linkages, and mechanisms using servo-driven axes where automatic and semi-automatic controls were replaced with fully automated cheap CNC technology. Lead screws were replaced with servo motors driven ball screws, and the tool post can be replaced with an automatic tool changer while the saddle can be reused and the use of mate/insert/screw to assemble ball guide ways. Thus, frictional dovetail guideways can be disabled to enable the use of linear ball rails-carriage slides in the structure of conventional lathe machine tools so that precision, accuracy, repeatability, and reliability can be upgraded considerably. The deficiency of relevant data acquisition for remanufacturing assessment modeling, machine tool remanufacturing experience, and comparative literature analysis can be applied. Such integrated analysis can help the uncertainty reduction approach simplify specific difficulties and adopt simplified methods, calculations, and criteria weighting. According to such integrated analysis, theoretical and practical models can be developed to obtain actual conditions and exact solutions (Abdullah, Abdulrazaq & Ghazi, 2020).

The conventional machine can be upgraded by using emerged cheap CNC technology to obtain the attributes of like-new performance, economic feasibility ensuring, education, training, and industry satisfying, accuracy and complex shape, reliability, and processing range and efficiency requirements satisfying can be within limits of standard CNC machine tools. Sustainable technological, economic and environmental developments can be obtained (Abdullah, 2020a).

Technological, economic, and environmental feasibilities were indexed by multiplying alternative performance weight by criteria weight of importance as integrated analyzing tools that deliver comparative literature and machine tool remanufacturing experience analysis. High innovative contribution potentials to deliver sustainable solutions satisfied the sustainability index 0.7 of conventional milling into CNC machine tool remanufacturing. The suitable literature comparatively to construct sustainability assessment modeling. To develop a triple-bottom sustainability approach, economic, environmental, and social pillars are of good contribution performance. Interlinked social and management pillars require more incentives to increase contribution to develop sustainability. A comprehensive sustainability assessment of remanufacturing machine tools was conducted by including criteria of cost, time, accuracy, reliability, processing efficiency, processing range, and ergonomics (Abdullah, 2020b).

The characteristics of remanufactured components should be considered to develop remanufacturing coefficients and a comprehensive evaluation system to allocate machine tools and specific reliability growth (Du et al., 2022).

Machine tool remanufacturing is a win-to-win energy-saving and environmentally benign strategy where a low-cost, like-new machine tool can be obtained. The original machine tool manufacturer and customers should be integrated within the remanufacturing business to satisfy profits and improve performance and after-sales service (Du et al., 2014).

Product life cycle characteristics should be integrated at various stages: materials selection, remanufacturing application, and remanufactured machine tool performance, maintenance, and economic and technical feasibilities (Liu et al., 2014).

The ultimate materials reusing and disassembly can predict the machine tool's state and life-reassembly remanufacturing application. To reduce the amount of new materials, redesign and more flexible reassembly techniques can be applied and developed (Gao & Wang, 2017).

Technical feasibility, economic feasibility, and environmental benefits can be integrated to evaluate remanufacturability. Disassembly, cleaning, inspection and sorting, part reconditioning, machine upgrading, and reassembly can be included with the technical feasibility of remanufacturing processes. The criterion of cost was used to evaluate the economic feasibility. Energy saving, material saving, and pollution reduction can evaluate and validate the environmental feasibility of remanufacturing machines into CNC machine tools (Du et al., 2012).

Remaining life conditions, matching analysis, remanufacturability evaluation, potential problems identification, redesign individualization, disassembly, cleaning, inspection classification and processing application, performance, reassembly, and inspection improvement. Significant

economic and social benefits and like-new turning machine tool remanufacturing can be achieved with better-upgraded performance. The supporting techniques should be modeled and contain an in-depth analysis of remanufacturing modeling. Decision-making analysis, including condition monitoring and diagnosis, can guarantee the remanufactured machine tool's capacities (Du et al., 2022).

The remanufacturing machine tool can achieve high added value, high technology content, high precision, and low surface roughness characteristics. Technical feasibility, economic feasibility, and resource environment feasibility can be included with remanufacturing modeling, imprecise and information remanufacturing evaluation, and the assessment of machine tool remanufacturing benefits and feasibilities. Better comprehensive benefits can get considerable benefits to reduce the potential risks in the remanufacturing process (Ling & He, 2020).

High-value-added circular economy recycling techniques can be satisfied through good-performance reassembly and agile remanufacturing of end-of-life machine tools, which are large in size, complex in structure, and high in added-value electromechanical equipment. Deterioration of accuracy, backward level of electrical control, and automation lead to high processing costs and low processing efficiency, which require conventional machine tools in CNC system remanufacturing to restore performance in like-new conditions by cutting cost and downtime so that a high remanufacturability index profitable and influential business remanufactured machine tools can be satisfied. Redesign and reconditioning are effectively managed by assessing remanufacturability by integrating cost, time, accuracy, reliability, processing efficiency, processing range, and ergonomics. The degree of performance recovery, function, and manufacturing capability restoring and updating based on remanufacturing conditions are satisfied. Economic, technical, environmental, and social objectives decision-making techniques can integrate various aspects, characteristics, decision-makers, and stakeholders. Thus, selecting technology to develop various remanufacturing processes can be involved in decision-making. Cost, quality, time, service, resource consumption, and environmental impact can be contained to estimate the feasibility and benefits. The computing decision-making approach can determine technical, economic, resource utilization, and environmental metrics of remanufacturability. Cost, disposed of items number, revenue, and after-remanufacturing performance satisfaction level can be used as multi-criteria decision-making remanufacturing problems to help identify remanufacturing options, cores acquiring, disassembly level, and cleaning techniques specifying (Du et al., 2020).

2. Method

A remanufacturability assessment model was developed to optimize alternative selection and apply a remanufacturing route to upgrade conventional surface grinding into CNC machines. Current CNC machine tools technology can cheaply help remanufacture conventional surface grinding machine tools to better waste-to-value management policy. The right quality and quantity of core machines to be remanufactured is already satisfied where the residual value is high and saved within the main machine body. The broken parts are limited to small ones that can be remanufactured by applying suitable remanufacturing techniques or replaced with new spare parts. Conventional surface grinding remanufacturing into like-new configuration and performance CNC machine tool can be obtained with upgraded automation capability of 2-axis to 5-axis.

Cost criteria are used to decide the best remanufacturing alternative of the seven developed alternatives through the description to develop the multi-criteria-based multi-alternatives decision-making problem.

The remanufacturing assessment methodology includes the following steps:

- 1- Conventional grinding machines analysis,
- 2- Conventional grinding machine configurations classification,
- 3- Upgrading scenarios description,
- 4- Conventional grinding remanufacturing alternatives description,
- 5- Conventional grinding remanufacturing evaluation criteria system establishing,
- 6- Evaluation criteria weighting,
- 7- Alternatives performances weighting,
- 8- Assessment matrix establishing,
- 9- Alternatives ranking,
- 10- Decision-making.

The remanufacturing description of conventional grinding into a CNC machine tool, Fig.1, can contain some or all of the following activities:

- 1- New CNC control wiring,
- 2- Spindle motor inventor assembly,
- 3- Ball screws assembly,

- 4- Servo motors assembly,
- 5- Servo drivers wiring,
- 6- Rotary table assembly,
- 7- Titling table assembly.

Figure 1: Conventional grinding into CNC machine tool remanufacturing



2.1. Criteria description

Comparative literature analysis (Abdullah et al., 2018; 2019; 2020; Du et al., 2012; 2022; Ling et al., 2020) and machine tool remanufacturing experience analysis were used to weight the importance of criteria and score the performance of alternatives and according to the following procedure:

2.1.1. Cost index (C)

Costs are all the required expenses to conduct remanufacturing. Four sub-criteria are used to calculate the cost index: conventional surface grinding machine cost, labor cost, and new parts and materials cost. Each criterion is of performance and importance weights, which can be defined as follows:

- Conventional surface grinding machine cost-based remanufactured machine weight (μ_{c1}),
- Labor cost-based remanufactured machine performance weight (μ_{c2}),
- New parts and materials cost-based remanufactured machine performance weight (μ_{c3}).

- Conventional surface grinding machine cost importance weight ($\omega_{\mu c1}$),
- Labor cost importance weight ($\omega_{\mu c2}$),
- New parts and material cost importance weight ($\omega_{\mu c3}$).

Conventional-to-conventional surface grinding into machine tool remanufacturing cost is the lowest but is of lower economic value compared with conventional-to-CNC surface grinding machine tool remanufacturing. Conventional surface grinding machine tool cost (μ_{c1}) is of low effect on the remanufacturing process since conventional surface grinding machine tools are very cheap. The highest remanufacturing performance is obtained by reducing the effect of labor cost (μ_{c2}) since skilled and high communication capability workers are required to learn, understand, and apply the CNC technology instructions. Emerged cheap CNC machine tools technology adoption enables new CNC parts and materials cost (μ_{c3}) to be easily satisfied so that it is of moderate effect on the remanufacturing process.

Cost index (C) is calculated by using equation (1) and according to the following constraints:

If $1.2 \leq C_{RCNC} / C_{RC} = 4$, then $C \geq 0.6$ so that $\mu_{c1} = 0.95$, $\mu_{c2} = 0.45-0.65$, $\mu_{c3} = 0.75-0.95$,
 If $0.25 \leq C_{RC} / C_{RCNC} < 0.6$, then $C < 0.6$ so that $\mu_{c1} = 0.45-0.65$, $\mu_{c2} = 0.45-0.65$, $\mu_{c3} = 0.45-0.65$

$$C = (\mu_{c1} * \omega_{\mu c1}) + (\mu_{c2} * \omega_{\mu c2}) + (\mu_{c3} * \omega_{\mu c3}) \quad (1)$$

Experience-based analysis of conventional surface grinding into CNC machine tool remanufacturing helps simplify equation (1) into:

$$C_1 = 0.1\mu_{C1} + 0.45\mu_{C2} + 0.25\mu_{C3}$$

Where:

$$\omega_{\mu C11} = 0.1, \omega_{\mu C12} = 0.45, \omega_{\mu C13} = 0.25,$$

C: cost index

C_{RCNC} : conventional surface grinding into CNC machine tool remanufacturing cost,

C_{RC} : conventional surface grinding into conventional machine tool remanufacturing cost,

μ_{C1} : conventional surface grinding machine tool cost on remanufacturing process effect weight,

$\omega_{\mu C1}$: conventional surface grinding machine tool cost importance weight,

μ_{C2} : labor cost of the remanufacturing process effect weight,

$\omega_{\mu C2}$: labor cost importance weight,

μ_{C3} : new CNC parts and materials cost on remanufacturing process effect weight,

$\omega_{\mu C3}$: new parts and material cost importance weight.

2.1.2. Time index (T)

Time is the required duration of remanufacturing. Heavy-weight machine tools are challenging to be subjected to reassembly-assembly processes, which require special equipment to carry and transmit the heavy masses of mechanical structure, which leads to a long remanufacturing cycle. Conventional surface grinding machine tools require less time to be remanufactured. Disassembly-assembly processes can reduce remanufacturing time compared to manufacturing new conventional surface grinding machine tools.

For end-of-life surface grinding machine tools, the main parts of high embodied technology can be restored, new spare parts can be easily provided, and the remanufacturing process can be planned very well so that remanufacturing time can be considerably more effective than new machine tool manufacturing or conventional to conventional surface grinding into machine tool remanufacturing time.

Time can be divided into components of disassembly time (μ_{T1}), assembly time (μ_{T2}), and new CNC parts and materials providing time (μ_{T3}).

Time components of importance weights include disassembly time importance weight ($\omega_{\mu T1}$), reassembly time importance weight ($\omega_{\mu T2}$), and new CNC parts and materials providing time importance weight ($\omega_{\mu T3}$).

The evaluation value of the remanufacturing time index (T) can be calculated by using equation (2) according to the following constraints:

$$\begin{aligned} \text{If } 1 \leq T_{RCNC} / T_{RC} < 2, \text{ then } T > 0.6 \text{ so that } \mu_{T1} = 0.95, \mu_{T2} = 0.75 - 0.85, \mu_{T3} = 0.75 - 0.95 \\ \text{If } 0.5 \leq T_{RC} / T_{RCNC} \leq 1, \text{ then } T < 0.6 \text{ so that } \mu_{T1} = 0.95, \mu_{T2} = 0.45 - 0.65, \mu_{T3} = 0.45 - 0.65 \end{aligned}$$

$$C_2 = (\mu_{T1} * \omega_{\mu T1}) + (\mu_{T2} * \omega_{\mu T2}) + (\mu_{T3} * \omega_{\mu T3}) \quad (2)$$

Experience-based analysis of conventional surface grinding into CNC machine tool remanufacturing helps simplify equation (2) into:

$$C_2 = 0.15\mu_{T1} + 0.6\mu_{T2} + 0.25\mu_{T3}$$

Where:

$$\omega_{\mu T1} = 0.15, \omega_{\mu T2} = 0.6, \omega_{\mu T3} = 0.25,$$

T: Time index

T_{RCNC} : conventional surface grinding into CNC machine tool remanufacturing time,

T_{RC} : conventional surface grinding into conventional machine tool remanufacturing time,

μ_{T1} : disassembly time in the remanufacturing process effect weight,

$\omega_{\mu T1}$: disassembly time importance weight,

μ_{T2} : reassembly time on the remanufacturing process effect weight,

$\omega_{\mu T2}$: reassembly time importance weight,

μ_{T3} : new CNC parts and materials time on remanufacturing process effect weight,

$\omega_{\mu T3}$: new CNC parts and materials providing time importance weight.

2.1.3. Accuracy index (A)

Accuracy is the measure of the expected short-term performance of a remanufactured tool. Increasing accuracy and complex 3D shape grinding ability can highlight new performance remanufacturing by satisfying geometric, positioning, and volumetric accuracies. Conventional grinding into CNC machine tool remanufacturing process effect to satisfy the required accuracy can be evaluated using the criteria of geometric accuracy (μ_{A1}), positioning accuracy (μ_{A2}), and volumetric accuracy (μ_{A3}). Remanufacturing process performance to upgrade like new reliable, accurate grinding CNC machine tool can be measured on a scale that reflects the remanufacturing difficulty, which is divided into five grades, including excellent, good, average, fair, and poor, with the corresponding values that vary according to the period (0-1) respectively.

Accuracy and complex shape components importance weights include geometric accuracy importance weight ($\omega_{\mu_{A1}}$), positioning accuracy importance weight ($\omega_{\mu_{A2}}$) and volumetric accuracy importance weight ($\omega_{\mu_{A3}}$). Accuracy and complex shape evaluation index (A) can be evaluated by equation (3):

$$A = (\mu_{A1} * \omega_{\mu_{A1}}) + (\mu_{A2} * \omega_{\mu_{A2}}) + (\mu_{A3} * \omega_{\mu_{A3}}) \quad (3)$$

In the case of grinding machine into CNC machine tool remanufacturing, equation (3) is simplified into:

$$A = 0.333\mu_{A1} + 0.333\mu_{A2} + 0.333\mu_{A3}$$

Where:

$$\omega_{\mu_{A1}} = 0.333, \omega_{\mu_{A2}} = 0.333, \omega_{\mu_{A3}} = 0.333$$

A: accuracy index,

μ_{A1} : geometric accuracy on remanufacturing process effect weight,

$\omega_{\mu_{A1}}$: geometric accuracy importance weight,

μ_{A2} : positioning accuracy in the remanufacturing process effect weight,

$\omega_{\mu_{A2}}$: positioning accuracy, importance weight,

μ_{A3} : volumetric accuracy on remanufacturing process effect weight,

$\omega_{\mu_{A3}}$: volumetric accuracy importance weight.

2.1.4. Reliability Index (R)

Reliability is the measure of the expected long-term performance of remanufactured machine tools. The mean time between failures is the measure of reliability, and as long as the meantime, the durability period of machine tool accuracy is high. Conventional grinding into CNC machine tool remanufacturing reliability can be evaluated by using the mean time between failures to lose the geometric accuracy (μ_{RA1}), the positioning accuracy (μ_{RA2}), and the volumetric accuracy (μ_{RA3}). Maintaining reliability for a long time can be measured on a scale divided into five grades include excellent, good, average, fair and poor with the corresponding values varying between (0.1-1). Mean time between failures to lose the geometric accuracy importance weight ($\omega_{\mu_{RA1}}$), lose the positioning accuracy importance weight ($\omega_{\mu_{RA2}}$), and the volumetric accuracy importance weight ($\omega_{\mu_{RA3}}$). The reliability index (R) can be evaluated by equation (4):

$$R = (\mu_{RA1} * \omega_{\mu_{RA1}}) + (\mu_{RA2} * \omega_{\mu_{RA2}}) + (\mu_{RA3} * \omega_{\mu_{RA3}}) \quad (4)$$

In the case of conventional grinding into CNC tool machine remanufacturing, equation (4) is simplified into:

$$R = 0.333\mu_{RA1} + 0.333\mu_{RA2} + 0.333\mu_{RA3}$$

Where:

R: Reliability index,

$\omega_{\mu_{RA1}} = 0.333, \omega_{\mu_{RA2}} = 0.333, \omega_{\mu_{RA3}} = 0.333,$

μ_{RA1} : mean time between failures to lose the geometric accuracy on remanufacturing process effect weight,

$\omega_{\mu_{RA1}}$: mean time between failures to lose the geometric accuracy importance weight,

μ_{RA2} : mean time between failures to lose the positioning accuracy on remanufacturing process effect weight,

$\omega_{\mu_{RA2}}$: mean time between failures to lose the positioning accuracy importance weight,

μ_{RA3} : mean time between failures to lose the volumetric accuracy on remanufacturing process effect weight,

$\omega_{\mu RA3}$: mean time between failures to lose the volumetric accuracy importance weight.

2.1.5. Processing shape complexity index (P)

Processing shape complexity is the ability and flexibility of a remanufactured grinding into a CNC machine to produce complex shape 3D models. The processing shape complexity can be improved by remanufacturing conventional grinding into a CNC machine tool where the machining time can also be reduced since cutting feed rates and spindle speeds can be highly increased by CNC remanufacturing, consequently decreasing the processing time considerably and increase the accuracy, complexity, and surface finish. The processing shape complexity index of remanufactured grinding into CNC machine tools can be expanded by increasing the number of controlled axes between 2 and 5 but with increased cost. Processing shape complexity index evaluation factors can be divided into the complexity of remanufacturing into 2-axis CNC grinding machine tool effect (μ_{P1}), 3-axis CNC grinding machine tool effect (μ_{P2}), 4-axis CNC grinding machine tool effect (μ_{P3}) and 5-axis CNC grinding machine tool effect (μ_{P4}). Processing shape complexity can be divided into five grades, including excellent, good, average, fair, and poor, with the corresponding values varying [0.1-1]. Processing shape complexity evaluation factors importance weights include remanufacturing into 2-axis CNC grinding machine tool importance weight ($\omega_{\mu P1}$), into 3-axis CNC grinding machine tool importance ($\omega_{\mu P2}$), into 4-axis CNC grinding machine tool importance ($\omega_{\mu P3}$) and into 5-axis CNC grinding machine tool importance ($\omega_{\mu P4}$). The processing shape complexity index (P) can be calculated using equation (5).

If $2 = P_{CNC} / P_C < 6$, then $P \geq 0.6$ so that $\mu_{P1}=0.85$, $\mu_{P2}=0.95$, $\mu_{P3}=0.45-0.65$, $\mu_{P4}=0.45-0.65$

If $1 = P_C / P_{CNC} < 2$, then $P < 0.6$ so that $\mu_{P1}=0.95$, $\mu_{P2}=0$, $\mu_{P3}=0$, $\mu_{P4}=0$

$$P = (\mu_{P1} * \omega_{\mu P1}) + (\mu_{P2} * \omega_{\mu P2}) + (\mu_{P3} * \omega_{\mu P3}) + (\mu_{P4} * \omega_{\mu P4}) \quad (5)$$

In the case of grinding into CNC machine tool remanufacturing, equation (5) is simplified into:

$$P = (0.3\mu_{P1}) + (0.5\mu_{P2}) + (0.1\mu_{P3}) + (0.1\mu_{P4})$$

Where:

P: Processing shape complexity index,

$\omega_{\mu P1}=0.3$, $\omega_{\mu P2}=0.5$, $\omega_{\mu P3}=0.1$, $\omega_{\mu P4}=0.1$

P_{CNC} : conventional grinding into CNC machine tool remanufacturing processing shape complexity,

P_C : conventional shaping into conventional machine tool remanufacturing processing shape complexity,

μ_{P1} : into 2-axis axis CNC grinding machine tool on remanufacturing process effect weight,

$\omega_{\mu P1}$: into 2-axis shaping machine tool importance weight,

μ_{P2} : into 3-axis CNC shaping machine tool on remanufacturing process effect weight,

$\omega_{\mu P2}$: into 3-axis CNC shaping machine tool importance weight,

μ_{P3} : into 4-axis CNC shaping machine tool on remanufacturing process effect weight,

$\omega_{\mu P3}$: into 4-axis CNC shaping machine tool importance weight,

μ_{P4} : into 5-axis CNC shaping machine tool on remanufacturing process effect weight,

$\omega_{\mu P4}$: into 5-axis CNC shaping machine tool importance weight.

2.1.6. Ergonomic index (E)

Ergonomics is the interaction among the operator, remanufactured machine into a CNC machine tool, and other system units through the manufacturing cell. The measures of the ergonomic index (E) can be divided into human-machine interaction (μ_{E1}), high safety (μ_{E2}), and maintainability (μ_{E3}). Ergonomic evaluation criteria effects on remanufacturing weight can be divided into five grades, including excellent, good, average, fair, and poor, with the corresponding values varying between [0.1-1]. Importance weights of criteria include human-machine interaction importance weight ($\omega_{\mu E1}$), safety importance weight ($\omega_{\mu E2}$), and maintainability importance weight ($\omega_{\mu E3}$). Ergonomic index (E) can be evaluated by equation (6):

$$E = (\mu_{E1} * \omega_{\mu E1}) + (\mu_{E2} * \omega_{\mu E2}) + (\mu_{E3} * \omega_{\mu E3}) \quad (6)$$

In the case of grinding into CNC machine tool remanufacturing, equation (6) is simplified into:

$$E=0.4\mu_{E1} + 0.3\mu_{E2} + 0.3\mu_{E3}$$

Where:

E: Ergonomic index

$\omega_{\mu E1}=0.4$, $\omega_{\mu E2}=0.3$, $\omega_{\mu E3}=0.3$,

μ_{E1} : human-machine interaction on remanufacturing process effect weight,

$\omega_{\mu E1}$: human-machine interaction importance weight,

μ_{E2} : safety in the remanufacturing process effect weight,

$\omega_{\mu E2}$: safety importance weight,

μ_{E3} : maintainability on remanufacturing process effect weight,

$\omega_{\mu E3}$: maintainability importance weight.

3. Remanufacturing alternatives description

3.1. A1: Conventional grinding into conventional machine tool

Conventional grinding into conventional machine tools contains the activities of:

- 1- Disassembling,
- 2- Sorting
- 3- Cleaning,
- 4- Worn parts replacing,
- 5- Electrical wiring,
- 6- Overall reassembly,
- 7- Testing.

3.2. A2: Conventional grinding into 2-axis CNC machine

Remanufacturing conventional grinding into a 2-axis CNC machine tool contains the activities of:

- 1- Disassembling,
- 2- Sorting,
- 3- Cleaning,
- 4- Worn parts Replacing,
- 5- Ball screw to machine Y-axis assembling,
- 6- Ball screw to machine Z-axis assembling,
- 7- Servo motors to Y-axis assembling,
- 8- Servo motors to Z-axis assembling,
- 9- CNC controller and servo drivers electrical wiring,
- 10- Rotating speed inverter to main spindle motor electrical wiring,
- 11- Overall reassembly,
- 12- Testing.

3.3. A3: Conventional grinding into a 3-axis CNC machine tool

Remanufacturing conventional grinding into a 3-axis CNC machine tool contains the activities of:

- 1- Disassembly,
- 2- Sorting,
- 3- Cleaning,
- 4- Worn parts replacing,
- 5- Ball screw to machine X-axis,
- 13- Ball screw to machine Y-axis assembling,
- 14- Ball screw to machine Z-axis assembling,
- 15- Servo motors to X-axis assembling
- 16- Servo motors to Y-axis assembling,
- 17- Servo motors to Z-axis assembling,
- 18- CNC controller and servo drivers electrical wiring,
- 19- Rotating speed inverter to main spindle motor electrical wiring,
- 20- Overall reassembly,
- 21- Testing.

3.4. A4: Conventional grinding into a 4-axis CNC machine tool

Remanufacturing conventional grinding into a 4-axis CNC machine tool contains the activities of:

- 1- Disassembly,
- 2- Sorting,
- 3- Cleaning,
- 4- Worn parts replacing,
- 5- Ball screw to machine X-axis,
- 6- Ball screw to machine Y-axis assembling,
- 7- Ball screw to machine Z-axis assembling,
- 8- Rotary table to machine A-axis assembling,
- 9- Servo motors to X-axis assembling
- 10- Servo motors to Y-axis assembling,
- 11- Servo motors to Z-axis assembling,
- 12- Servo motors to A-axis assembling,
- 13- CNC controller and servo drivers electrical wiring,
- 14- Rotating speed inverter to main spindle motor electrical wiring,
- 15- Overall reassembly,
- 16- Testing.

3.5. A5: Conventional grinding into a 5-axis CNC tool machine

Remanufacturing conventional grinding into a 5-axis CNC machine tool contains the activities of:

- 1- Disassembly,
- 2- Sorting,
- 3- Cleaning,
- 4- Worn parts replacing,
- 5- Ball screw to machine X-axis,
- 6- Ball screw to machine Y-axis assembling,
- 7- Ball screw to machine Z-axis assembling,
- 8- Rotary table to machine A-axis assembling,
- 9- Tilting table to machine B-axis assembling,
- 10- Servo motors to X-axis assembling
- 11- Servo motors to Y-axis assembling,
- 12- Servo motors to Z-axis assembling,
- 13- Servo motors to A-axis assembling,
- 14- Servo motors to B-axis assembling ,
- 15- CNC controller and servo drivers electrical wiring,
- 16- Rotating speed inverter to main spindle motor electrical wiring,
- 17- Overall reassembly,
- 18- Testing.

4. Assessment matrix

Technical feasibility index (T), economic benefits index (C), and environmental benefits index (E) are the three components of remanufacturability which follow the thresholds of ($0.6 \leq T = 1$, $0.6 \leq C = 1$ and $0.7 \leq E = 1$). By conducting machine tool remanufacturing, at least good performance can be satisfied over the above-mentioned thresholds for technical feasibility and economic and environmental benefits. The technical feasibility index can be greater than 0.6, and the economic benefits index, while the environmental benefits index, can be as high as 0.7 (Du et al., 2012).

The assessment matrix can be constructed according to the following assumptions (Abdullah et al., 2018; 2019; 2020; Du et al., 2012; 2022; Ling et al., 2020):

Given:

A set of alternatives:

$A: \{A_1, A_2, A_3, \dots, A_n\}$

A set of criteria:

$C: \{C_1, C_2, C_3, \dots, C_n\}$

A set of performances:

$P: \{P_{11}, \dots, P_{ij}\}$

Equation (7) is used to find the alternative-criteria performance score:

$$P = \mu_{Wi} * \omega_{\mu Wj} \tag{7}$$

Where:

P= alternative performance score,

μ_{Wi} = alternative effect weight,

$\omega_{\mu Wj}$ = criteria importance weight,

$i=(1,2,3,\dots,m)$, $m=6$,

$j=(1,2,3,\dots,k)$, $k=6$.

Table 1: Remanufacturability Alternatives Assessment

Index	Performance (A1)	Performance (A2)	Performance (A3)	Performance (A4)	Performance (A5)
Cost(C)	$P_{11}=0.68$	$P_{11}=0.70$	$P_{11}=0.72$	$P_{11}=0.74$	$P_{11}=0.81$
Time(T)	$P_{12}=0.68$	$P_{12}=0.70$	$P_{12}=0.77$	$P_{12}=0.84$	$P_{12}=0.86$
Accuracy and complex shape(A)	$P_{13}=0.50$	$P_{13}=0.60$	$P_{13}=0.70$	$P_{13}=0.76$	$P_{13}=0.80$
Reliability (R)	$P_{14}=0.50$	$P_{14}=0.60$	$P_{14}=0.70$	$P_{14}=0.80$	$P_{14}=0.90$
Processing range and efficiency (P)	$P_{15}=0.08$	$P_{15}=0.24$	$P_{15}=0.36$	$P_{15}=0.40$	$P_{15}=0.52$
Ergonomic (E)	$P_{16}=0.52$	$P_{16}=0.60$	$P_{16}=0.68$	$P_{16}=0.68$	$P_{16}=0.76$
Summation of Performances (ΣP_{ij})	2.96	3.44	3.93	4.22	4.65
RI	0.637	0.740	0.845	0.908	0.999
Technical feasibility index	0.6	0.68	0.76	0.83	0.91
Economic feasibility index	0.6	0.68	0.76	0.83	0.91
Resources and Environmental Benefits Index	0.7	0.78	0.86	0.93	0.93
Rank	5	4	3	2	1

Assessment-based ranks constraints:

- 1- The servo-driven X-axis, servo-driven Y-axis, and servo-driven Z-axis mechanism, Figure 2, is absolutely very important,

Figure2: Servo-driven X-axis, servo-driven Y-axis, and servo-driven Z-axis mechanism



- 2- Hydraulic sliding X-axis, servo-driven Y-axis, and servo-driven Z-axis mechanism, Figure 3, is much more important,

Figure 3: Hydraulic sliding X-axis, servo-driven Y-axis, and servo-driven Z-axis mechanism



- 3- The servo-driven X-axis, servo-driven Y-axis, servo-driven Z-axis, and servo-driven A-axis mechanism are much more important,
- 4- The servo-driven X-axis, servo-driven Y-axis, servo-driven Z-axis, servo-driven A-axis, and servo-driven B-axis mechanism is more important,
- 5- Hydraulic sliding X-axis, automatically driven Y-axis, and Z-axis mechanism (Fig. 4) are essential.

Figure 4: Hydraulic sliding X-axis, automatically driven Y-axis and Z-axis mechanism



Alternative normalized weight is calculated by using equation (8) by multiplying the summation of performances of an alternative. Descending value of technical feasibility, economic feasibility, and resource and environmental benefits with reducing the functionality according to assessment-based ranks constraints.

The remanufacturability index (RI), Table 1, of conventional grinding into CNC machine tool remanufacturing varies between (RI=0.637-0.999).

Using emerged cheap CNC technology will convert the remanufacturing paradigm to dominate cost and time effectiveness of reassembly processes remanufacturing over conventional grinding into conventional machine tool remanufacturing.

By comparing a conventional grinding machine with a 2-axis CNC machine tool of a single hydraulic automatic X-axis grinding machine tool, it is obvious to recognize the

Dramatic changes in grinding machine tool performance can be observed where very high enhancements can be obtained in accuracy, shape complexity, grinding function, reliability, processing range, and efficiency.

The grinding machine is remanufactured into an independent machine tool instead of a surface grinding by-process machine tool for multiple purposes.

$$RI = \Sigma P_{ij} / \Sigma P_{km} \quad (8)$$

Where:

RI = normalized performance weight,

ΣP_{ij} = summation of performances of any alternative,

ΣP_{km} = summation of performances of absolute more critical alternative.

5. Discussion

Assessment criteria should be considered simultaneously to develop the performance criteria that interact with alternative evaluation as an integrated solution. The developed decision-making problem is to rank five different alternatives, varying from conventional grinding into conventional machine tool remanufacturing to conventional grinding into 5-axis CNC machine tool remanufacturing.

Impacts on the function, performance, quality, reliability, and characteristics of remanufactured machine tools should be modeled to evaluate the maximum comprehensive benefits. Such factors should be developed into criteria to evaluate technical feasibility through interacting economic feasibility with resources and environmental benefits.

Remanufacturability assessment criteria are divided into three interconnected groups of criteria to help improve technical performance to develop environmental high-added value at a relatively low cost where criteria include (Du et al., 2020):

- 1- Technical feasibility criteria,
- 2- Economic feasibility criteria,
- 3- Resource and environmental benefits criteria,

Literature analysis (Qin et al., 2023; Abdullah et al., 2018; 2019; 2021; 2022) and machine tool remanufacturing experience analysis were used to conclude the remanufacturability. The alternatives assessment matrix is shown in Table 1. Alternatives ranking follows $A_5 > A_4 > A_3 > A_2 > A_1$.

6. Conclusion

In conclusion, this study presents a multi-criteria assessment methodology to evaluate the remanufacturability of conventional surface grinding machines into CNC machine tools. The Remanufacturability Index (RI) is proposed as a quantitative measure incorporating technical, economic, and environmental criteria.

The results show that remanufacturing conventional grinding machines into CNC configurations is feasible, with the RI ranging from 0.637 for 2-axis to 0.999 for 5-axis configurations. Higher-axis CNC remanufactured machines demonstrate greater remanufacturability. The methodology provides a structured approach for manufacturers to assess the potential benefits and challenges of upgrading their conventional machines with CNC technology.

From a practical perspective, the proposed methodology can guide decision-making for small and medium-sized manufacturers considering machine tool remanufacturing. It allows them to evaluate different upgrade scenarios and prioritize investments based on the RI. Remanufacturing presents an opportunity to cost-effectively enhance the capabilities and sustainability of their machine tool fleet.

Scientifically, this study contributes to the growing field of sustainable manufacturing and circular economy. It extends the application of multi-criteria decision-making methods to machine tool remanufacturing. The Remanufacturability Index offers a new tool for researchers to quantify and compare the potential for remanufacturing different machine configurations.

Future research should focus on validating the proposed methodology with case studies in various industrial settings. The model could be refined based on empirical data and expert feedback. Sensitivity analysis can be conducted to understand the impact of different criteria weights on the RI. Integrating the methodology into decision support systems can make it more accessible to practitioners.

This study lays the groundwork for systematically evaluating machine tool remanufacturing potential. It highlights the sustainability benefits of extending the useful life of conventional machines through CNC upgrades. With further development and adoption, such remanufacturing practices can contribute significantly to the circular economy in the manufacturing sector.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The data are available on request.

Competing interests

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