Conventional Shaping into CNC Machine Tool Remanufacturability Assessment

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Authors' contributions

This work was carried out in collaboration among all authors. Author ZTA designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors EMM and AZR managed the analyses of the study. Authors SSG and EAA managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Aims: Remanufacturability Index (RI) was calculated to indicate the ability of remanufacturing conventional shaping into CNC machine tool through multi-criteria assessment methodology.
Place and Duration of Study: Middle Technical University, Institute of Technology-Baghdad, Mechanical Techniques School, between 2021/2022.
Methodology: Conventional shaping machines which are remanufactured-upgraded into CNC machine tools were analyzed to classify a group of seven remanufacturing-upgrading alternatives. Multi-criteria were defined include cost, time, accuracy and complex shape, reliability, processing range and efficiency and ergonomic. Weighting of importance of criteria and performance of alternatives were conducted by applying comparative literature analysis and machine tool remanufacturing experience analysis of mechanical structure of remanufactured-upgraded conventional shaping into CNC machine tool as well as alternatives performances scoring.
Results: As many as the number of automated axes, as high as the Remanufacturability Index (RI) which is dedicated to remanufactured-upgraded conventional shaping into 2-axis to 5-axis CNC machine tool.
Conclusion: Remanufactured-upgrading conventional shaping into CNC machine tool is of high remanufacturing potentials that satisfy conditions of technical, economic and environmental feasibilities.

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1. INTRODUCTION

Closed loop sustainable manufacturing-remanufacturing of vertical turret milling machine was studied to assess the ability of integrating the educational institutions to conduct remanufacturing of machine tools as a business. Purchased new parts and material and emerged cheap CNC technology were modeled to develop energy consumption and CO_2 emissions criteria to help conclude feedbacks about environmental benefits. Remanufacturing processes were reduced to be agile and contain disassembly, cleaning and reassembly without any need for high skilled mechanical processing activities. To conduct more flexible reassembly, eco-design was applied to develop modules of linear slides rails-carriages and ball lead screws to be reassembled to conventional vertical turret milling machine tool. More flexible reassembly was certain through magnetic pots based mechanical interface. Comparative eco-audit of remanufacturing portfolio to embed emerged cheap CNC technology within conventional vertical turret milling machine tool structure was conducted to optimize eco-innovation strategy to deliver sustainable remanufacturing. Machine tool remanufacturing which is based on both emerged cheap CNC technology adoption and capabilities of educational institutions, where the hybrid labor-student remanufacturing environment can be certain to deliver hybrid public-private services that were aimed to establish triple bottoms sustainability of economic, environmental and social pillars [1]. Sustainability modeling to study possibility of proposing several remanufacturing alternatives of conventional lathe into CNC machine tool was conducted. Multi-alternatives based conventional lathe machine tool remanufacturing sustainability was modeled to produce CNC machine tool. Conventional lathe into CNC machine remanufacturing-upgrading is flexible reassembly based agile portfolio, where automatic and semi-automatic controls were replaced with fully automated emerged cheap CNC technology to eliminate gearboxes, linkages and mechanisms by using of servo motorized axes. In both forward and transvers directions lead screws were replaced with motorized ball screws. Also tool post can be replaced with automatic tool changer while saddle can be reused. The key technology is the use of mate/insert/screw to assembly ball

guide ways to disable dovetail guide ways to embed emerged cheap CNC technology rails-carriages to structure of conventional lathe machine tool by remanufacturing so that precision, accuracy, repeatability and reliability can be enhanced considerably. Comparative literature analysis and machine tool remanufacturing experience analysis can substitute the leak of relevant data acquisition to assess remanufacturing-upgrading modeling. Such uncertainty reduction approach can enable simplify certain difficulties and adopt simplified methods, calculations and criteria weighting so that theoretical and practical models can be developed into actual conditions exact solution [2]. Huge amount of milling machines are out of date due to high development in CNC machines so that to cope with such problem, conventional milling machines can be upgraded by using emerged cheap CNC technology which is of attributes of [3]:

• Like-new performance can be obtained,

• Economic feasibility can be certain,

• Education, training and industry purposes can be satisfied,

• Accuracy and complex shape, reliability and processing range and efficiency requirements can be within limits of standard CNC machine tools,

• Sustainability can be obtained with technological, economic and environmental developments.

Comparative literature and machine tool remanufacturing experience were applied as analyzing tools to find the indexes of technological, economic and environmental developments where assessment feasibilities can be calculated through multiplication of performance weight by weight of importance. Sustainability index of 0.7 was calculated to refer to that conventional milling machine is of high innovative contribution potentials to deliver sustainable solution of CNC machine tool remanufacturing. Sustainability assessment models in field of remanufacturing-upgrading are reviewed and modified to accommodate new changes that accompany conventional machine

tool into CNC machine remanufacturing-upgrading. Experience was used to project the suitable literature comparatively to construct sustainability assessment modeling. For the current case study, economic, environmental and social pillars are of good contribution performance to develop a triple bottoms sustainability approach. Social and management pillars are interlinked and require more incentives to increase contribution to develop sustainability .A group of criteria are selected to conduct comprehensive sustainability assessment of remanufacturing-upgrading process include remanufacturing cost, remanufacturing time, accuracy, reliability, processing efficiency, processing range and ergonomics [4].

Remanufactured NC gear hobbing machine tools allocation is of reliability growth target that can be achieved through the proposed remanufacturing comprehensive evaluation system and the remanufacturing coefficient that takes into account the characteristics of remanufactured components [5].

For both of customers and remanufacturers, machine tool remanufacturing is a win-to-win energy saving and environmental benign paradigm. Like-new machine tool at a low cost in short time can be obtained by the customers and remanufacturing can be performed by the original machine tool manufacturer to improve after sale service and conduct machine tool remanufacturing business to obtain profits [6].

More flexible assembly for remanufacturing can be achieved by modular design to facilitate product disassembly-remanufacturing-reassembly where various aspects are needed to be integrated include product life cycle characteristics at various stages, materials aspects selection, performance of remanufacturing, performance using, performance maintenance, economic feasibility and technical feasibility [7].

Machine state and remaining life can be predicted through reliable analytical modeling. To ultimate materials reuse, disassembly-remanufacturing-reassembly can be applied. Redesign methods can also be applied to reduce the amount of new materials to be used [8], and more flexible reassembly techniques can be developed.

Remanufacturability was evaluated by integrating technological feasibility, economic feasibility and environmental benefits. Technological feasibility varies with remanufacturing processes that include disassembly, cleaning, inspection and sorting, part reconditioning, machine upgrading and reassembly. Cost was used as the criterion to evaluate the economic feasibility. Energy saving, material saving and pollution reduction represent the criteria to evaluate the environmental feasibility. The remanufacturing of machine tool into CNC machine is feasible and validate [9].

Machine tool remanufacturing can include [10]:

- Monitoring and diagnosis of remaining life conditions,
- Matching analysis,
- Remanufacturability evaluation,
- Potential problems identification,
- Redesign individualization,
- Disassembly, cleaning, inspection classification and processing application,
- Performance, reassembly and inspection improvement.

Better performance of upgraded like-new turning machine tool can be achieved with great economic and social benefits. Remanufacturing modeling should contain in-depth analysis of the supporting technologies such as condition monitoring and diagnosis and decision-making analysis to guarantee the production capacities of machine tools [10].

High added value, high technology content and great remanufacturing value are the characteristics of grinding machine tool to achieve high precision and low surface roughness. Remanufacturing evaluation was based on imprecise and fuzzy information to assess various feasibilities and benefits. Grinder machine tool remanufacturing modeling was established to include criteria of technical feasibility, economic feasibility and resource environment feasibility. Remanufacturing of grinding machine tool can obtain better comprehensive benefits and can get considerable benefits and reduce the potential risks in the remanufacturing process [11].

Reassembly agile remanufacturing is of good performance and represents high value-added circular economy recycling technique for end-of-life machine tools. Machine tools are electromechanical equipment of large size, complex structure and high value at the end-of-life and in service to provide key manufacturing

capabilities. Machine tools suffer potential problems as service time increases such as deterioration of accuracy, backward level of electrical control and automation that lead to high processing costs and low processing efficiency which require remanufacturing-upgrading into CNC system to restore like-new conditions performance [12].

High remanufacturability index can be satisfied by remanufacturing machine tool by cutting cost and downtime so that remanufacturing machine tool is profitable and influential business. Conditions of machine tools, redesign scheme and reconditioning process are effectively managed through assessing remanufacturability by integrating criteria of cost, time, accuracy, reliability, processing efficiency, processing range and ergonomics so that product based remanufacturing conditions are satisfied to the degree of performance recovering , function and manufacturing capability restoring and updating. Multiple objectives decision-making methods of multiple economic, technical, environmental and social criteria can integrate various aspects, characteristics, decision makers and stakeholders to develop and involve problems of various processes of remanufacturing for technology selecting to estimate and score the feasibilities and benefits that contain cost, quality, time, service, resource consumption and environmental impact. Technological, economic, resource utilization and environmental metrics determined remanufacturability is a fuzzy computing decision making approach. Cost, disposed items number, revenue and after remanufacturing performance satisfaction level are criteria that can be used to develop multi-criteria decision making problem. Multiple remanufacturing activities evaluation to optimize remanufacturing outcomes by identifying remanufacturing options, cores acquiring, disassembly level, cleaning techniques and group technology based product commonality [12].

Remanufacturability can be divided into three components include technical feasibility, economic and environmental benefits. Thresholds of remanufacturability components indexes should be 0.6< = technical feasibility =1, 0.6 < = economic benefits =1 and 0.7 < = environmental benefits =1.Technical feasibility and economic and environmental benefits are good by conducting machine tool remanufacturing. Environmental benefits index can be greater than 0.6 as well as the economic benefits index while environmental benefits index is as high as to be greater than 0.7 [9].

Quality function deployment and fuzzy linear regression can describe the functional relationships between remanufacturing performance and process quality characteristics to obtain the optimal solution. Conceptual product development phase integrated remanufacturing is decision making problems development process to optimize major strategic factors that enable effective remanufacturing decisions early. Economic and environmental impacts are quickly assessing measures for decision making to compare remanufacturing as an attractive choice comparing with producing new product. Fault features and quantified damage degrees can be used to plan remanufacturing process optimization. Product design with remanufacturability numerical metrics integration is an informative design features assessment system to be built on consideration of disassembly accessibility, product complexity and recoverability [12].

Virtual remanufacturing research areas can include remanufacturing processes development, remanufacturing sustainability assessment, remanufacturability assessment, remanufacturing feasibility evaluation , core acquisition management, non-destructive testing for remanufacturing and remanufacturing inventory management. Remanufacturing is an original equipment manufacturer driven decision making problems that their benefits criteria weighting process is directly affected with the variable nature of personalized and customized solutions. Product life cycle and consumer psychology are of impact on decision making which can be modeled to determine the optimal price and production quantity of remanufactured machine tools [12].

2. REMANUFACTURING-UPGRADING ASSESSMENT METHODOLOGY

From literature review and analysis, it is concluded that most of the relevant literature focuses on the decision making for remanufacturing as well as optimum remanufacturing alternative selection process which is mainly includes economic, technical and environmental factors. Remanufacturability assessment can provide the required models to optimize alternative selection out of a pool of remanufacturing portfolios and new product based remanufacturing development.

Emerged cheap CNC machine tools technology can enable remanufacturing of small and medium sized conventional machine tools so their little value and the remanufacturing benefits will be very significant for educational institutions and small workshops stakeholders. Acquiring the right amounts of cores is already satisfy whatever the situation of end-of-life machine tool unless the fault degree reaches the broken of parts and applying suitable remanufacturing techniques is satisfied through assembly aided remanufacturing. The problem description states that developing the used conventional shaping machine into like-new performance of CNC machine tool, Fig. 1, instead of appearance, with upgraded automation capability of 2-axis to 5-axis and compare them with conventional to conventional shaping machine remanufacturing to decide the best remanufacturability alternative of the developed seven alternatives through a multi-criteria and multi-alternatives decision making problem. Assessment methodology includes the following steps:

- Reviewed the state of the art in tools and techniques used to conduct machine tool remanufacturing,
- Identifying selection influences to determine the reasonable alternatives,
- Machine tool remanufacturing alternatives description,
- Machine tool remanufacturing evaluation criteria system establishing,
- Decision-making modeling and evaluation criteria weighting,
- Alternatives performances verifying and analyzing,
- Assessment matrix establishing ,
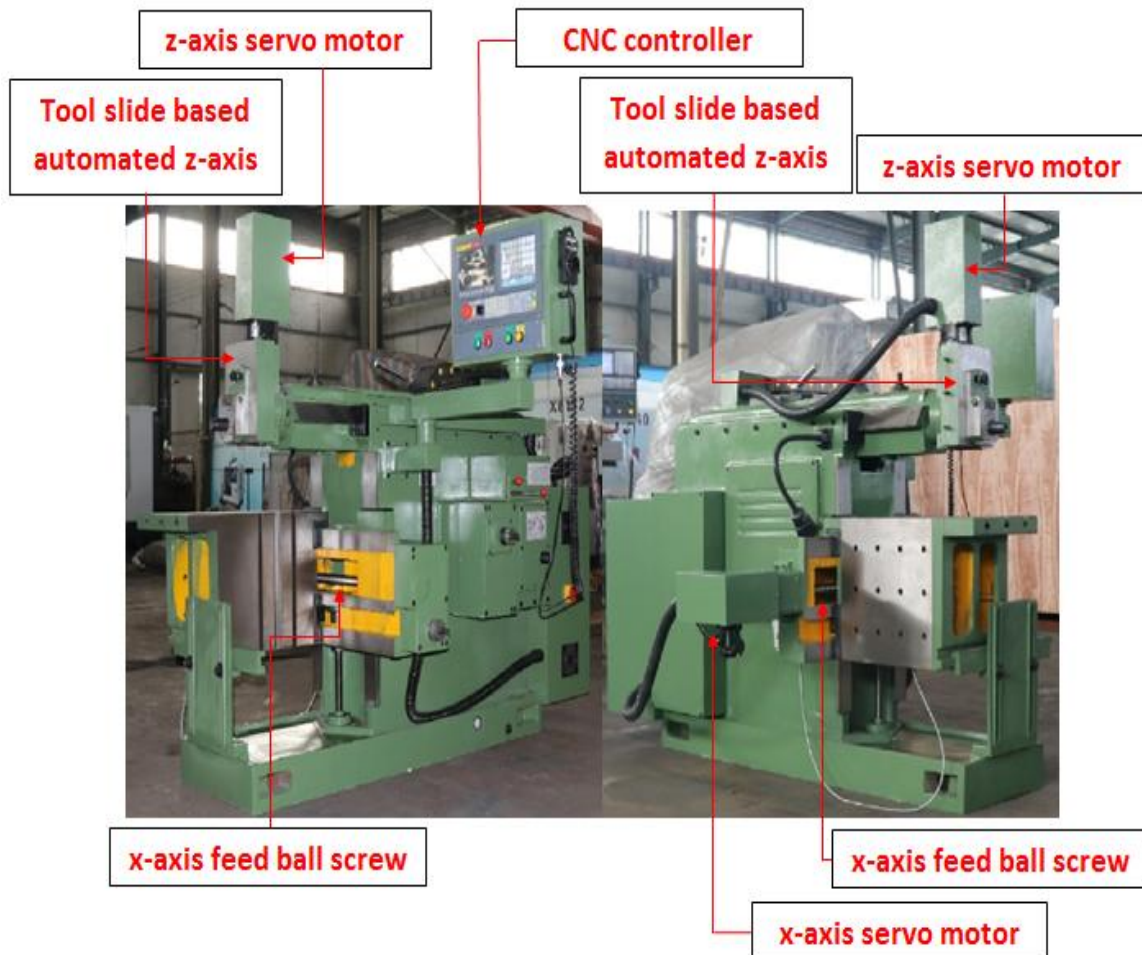- Alternatives ranking.

Fig. 1. Conventional shaping machine into 2- axis CNC machine tool remanufacturing
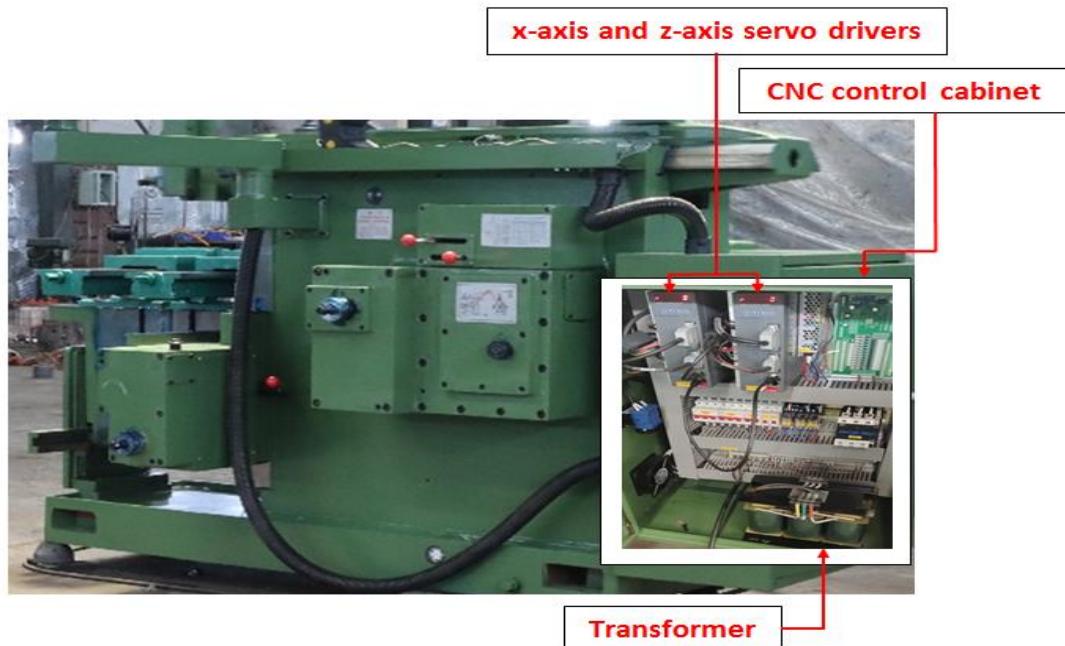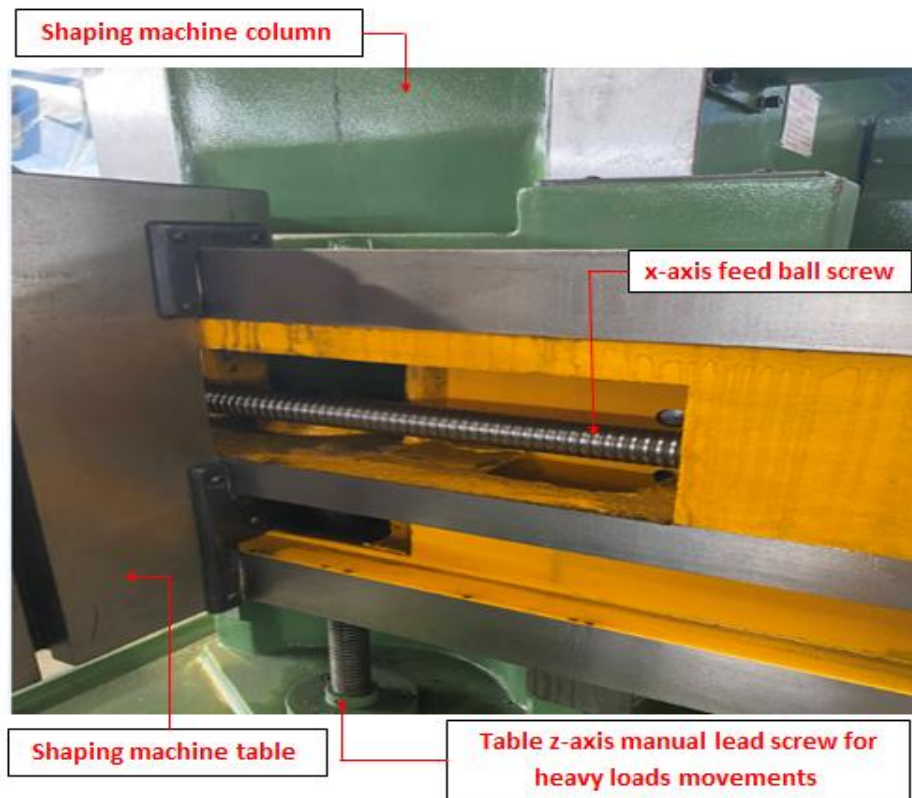
Fig. 2. CNC control cabinet

Fig. 3. Ball screw assembling to conventional shaping to convert it into CNC machine tool

The damage of components and parts of machine tools is limited to rotating parts mainly and to sliding part secondarily so that reassembly based remanufacturing conventional shaping into CNC machine tool can contain the following activities:

1- CNC control to be used such as GSK, KND, NaiWei or Xinkeyuan, ,Fig. 1,
2- Servo motors and drivers to be used, Fig. 2,
3- Ball screws quality to be used, Fig. 3,
4- Ball railways using applicability,
5- Number of axes to be CNC based automated.

2.1 Criteria Description

Comparative literature analysis [1-4,6,9-15] 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_1)

Shaping machine tools weight has negative effect on remanufacturing cost but machine embodied technology has the most positive impact on remanufacturability so that the cost can be divided into components of conventional shaping machine tool price and disassembly cost percentage of total remanufacturing cost (μ_{C11}), labor cost percentage of total remanufacturing cost (μ_{C12}) and purchased new CNC parts and materials cost of percentage of total remanufacturing cost (μ_{C13}). Cost components importance weights include conventional machine tool cost importance weight ($\omega_{\mu C11}$), labor cost importance weight ($\omega_{\mu C12}$) and purchased new parts and material costs importance weight ($\omega_{\mu C13}$). Conventional-to-conventional shaping into machine tool remanufacturing cost is the lowest but it is not economic delivered solution. Low effect on performance of machine tool reassembly aided remanufacturing process is of conventional shaping machine tool price and disassembly cost. The highest remanufacturing performance is obtained by reduction labor cost (μ_{C12}) since skilled and of high communication capability workers are required to learn, understand and apply the CNC technology instructions. Moderate effect on performance of machine tool remanufacturing process is of purchased new CNC parts and materials cost which can be easily satisfied by adoption of emerged cheap CNC machine tools technology. The performance and importance of cost index (C_1) components are conducted according to equation (1) and to the following constraints:

If $1.2 <= C_{1RCNC} / C_{1RC} = 4$, then $C_1 >= 0.6$ so that $\mu_{c11} = 0.95$, $\mu_{c12} = 0.75-0.95$, $\mu_{c13} = 0.75-0.95$

If $0.25 <= C_{1RC} / C_{1RCNC} < 0.6$, then $C_1 < 0.6$ so that $\mu_{c11} = 0.95$, $\mu_{c12} = 0.45-0.65$, $\mu_{c13} = 0.45-0.65$

$$C_1 = (\mu_{c11} * \omega_{\mu c11}) + (\mu_{c12} * \omega_{\mu c12}) + (\mu_{c13} * \omega_{\mu c13}) \tag{1}$$

In case of small-to-medium size machine tool remanufacturing, equation (1) is simplified into:

$$C_1 = 0.1\mu_{C11} + 0.7\mu_{C12} + 0.2\mu_{C13}$$

Where:

$\omega_{\mu C11} = 0.1$, $\omega_{\mu C12} = 0.7$, $\omega_{\mu C13} = 0.2$,
C_{1RCNC}: conventional shaping into CNC machine tool remanufacturing cost,
C_{1RC}: conventional shaping into conventional machine tool remanufacturing cost,
μ_{c11}: conventional shaping machine tool price and disassembly cost percentage of total remanufacturing cost,
$\omega_{\mu c11}$: conventional machine tool cost and disassembly cost importance weight,
μ_{c12}: labor cost percentage of total remanufacturing cost,
$\omega_{\mu c12}$: labor cost importance weight,
μ_{c13}: purchased new CNC parts and materials cost percentage of total remanufacturing cost,
$\omega_{\mu c13}$: purchased new parts and material cost importance weight.

2.1.2 Time index (C_2)

Heavy weights machine tools are difficult to be subjected to reassembly aided remanufacturing process since they require special equipment to carry and transmit the heavy masses of mechanical structure which leads to long remanufacturing cycle. Small-to-medium size machine tools require lower time thresholds to be subjected to remanufacturing. Assembly aided remanufacturing can significantly reduce remanufacturing time compared to traditional like-new remanufacturing or new machine tool manufacturing. End-of-life degree of main parts of machine tool of high embodied technology can be easily provided and the remanufacturing process can be planned very well so that remanufacturing time can be considerably effective than new machine tool manufacturing or conventional to conventional shaping into machine tool remanufacturing time. Time can be divided into components of disassembly time (μ_{C21}), assembly time (μ_{C22}) and purchased new CNC parts and materials time (μ_{C22}). Time components importance weights include

disassembly time importance weight ($\omega_{\mu C21}$), reassembly time importance weight ($\omega_{\mu C22}$) and purchased new CNC parts and materials time importance weight ($\omega_{\mu C23}$). The evaluation value of remanufacturing time index (C_2) can be calculated by using equation (2) according to the following constraints:

If $1 <= C_{2RCNC} / C_{2RC} < 2$, then $C_2 >= 0.6$ so that $\mu_{C21} = 0.95$, $\mu_{C22} = 0.75\text{-}0.85$, $\mu_{C23} = 0.75\text{-}0.95$

If $0.5 <= C_{2RC} / C_{2RCNC} <= 1$, then $C_2 < 0.6$ so that $\mu_{C21} = 0.95$, $\mu_{C22} = 0.45\text{-}0.65$, $\mu_{C23} = 0.45\text{-}0.65$

$$C_2 = (\mu_{C21} * \omega_{\mu C21}) + (\mu_{C22} * \omega_{\mu C22}) + (\mu_{C23} * \omega\mu_{C23}) \quad (2)$$

In case of small-to-medium size machine tool remanufacturing, equation (2) is simplified into:
$C_2 = 0.1\mu_{C21} + 0.7\mu_{C22} + 0.2\mu_{C23}$

Where:

$\omega_{\mu C21} = 0.1$, $\omega_{\mu C22} = 0.7$, $\omega_{\mu C23} = 0.2$,
C_{2RCNC}: conventional shaping into CNC machine tool remanufacturing time,
C_{2RC}: conventional shaping into conventional machine tool remanufacturing time,
μ_{C21}: disassembly time percentage of total remanufacturing time,
$\omega_{\mu C21}$: disassembly time importance weight,
μ_{C22}: reassembly time percentage of total remanufacturing time,
$\omega_{\mu C22}$: reassembly time importance weight,
μ_{C23}: purchased new CNC parts and materials time percentage of total remanufacturing time,
$\omega_{\mu C23}$: purchased new CNC parts and materials time importance weight.

2.1.3 Accuracy and complex shape index (C_3)

By satisfying geometric, positioning and volumetric accuracies, like new performance can be restored by reassembly aided remanufacturing to certain both of upgraded accuracy and complex shapes cutting ability. Accuracy and complex shape evaluation of shaping into CNC machine tool remanufacturing can be evaluated by using the performance measures of remanufacturing to satisfy geometric accuracy (μ_{C31}), remanufacturing to satisfy positioning accuracy (μ_{C32}) and remanufacturing to satisfy volumetric accuracy (μ_{C33}). Reassembly aided remanufacturing performance to upgrade like new reliability can be measured on scale that is divided into five grades include excellent, good, average, fair and poor with the corresponding values of 0.2, 0.4 , 0.6, 0.8 and 1 respectively. Accuracy and complex shape components importance weights include geometric accuracy importance weight ($\omega_{\mu C31}$), positioning accuracy importance weight ($\omega_{\mu C32}$) and volumetric accuracy importance weight ($\omega_{\mu C33}$). Accuracy and complex shape evaluation index (C_3) can be evaluated by equation (3):

$$C_3 = (\mu_{C31} * \omega_{\mu C31}) + (\mu_{C32} * \omega_{\mu C32}) + (\mu_{C33} * \omega_{\mu C33}) \quad (3)$$

In case of small-to-medium size machine tool remanufacturing, equation (3) is simplified into:

$$C_3 = 0.5\mu_{C31} + 0.3\mu_{C32} + 0.2\mu_{C33}$$

Where:

$\omega_{\mu C31} = 0.5$, $\omega_{\mu C32} = 0.3$, $\omega_{\mu C33} = 0.2$,
μ_{C31}: performance of remanufacturing to satisfy geometric accuracy,
$\omega_{\mu C31}$: geometric accuracy importance weight,
μ_{C32}: performance of remanufacturing to satisfy positioning accuracy,
$\omega_{\mu C32}$: positioning accuracy importance weight,
μ_{C33}: performance of remanufacturing to satisfy volumetric accuracy,
$\omega_{\mu C33}$: volumetric accuracy importance weight.

2.1.4 Reliability index (C_4)

As long as the mean time between failures, as high as the reliability, which is the durability period of machine tool accuracy. Reliability evaluation of shaping into CNC machine tool remanufacturing can be evaluated by using the performance measures of reassembly aided remanufacturing to satisfy high mean time between failures to lose the geometric accuracy (μ_{C41}), remanufacturing to satisfy high mean time between failures to lose the positioning accuracy (μ_{C42}) and remanufacturing to satisfy high mean time between failures to lose the volumetric accuracy (μ_{C43}). Reassembly aided remanufacturing performance to maintain reliability for long time can be measured on a scale that is divided into five grades include excellent, good, average, fair and poor with the corresponding values of 0.2, 0.4 , 0.6, 0.8 and 1 respectively. Reliability components importance weights include high mean time between failures to lose the geometric accuracy importance weight ($\omega_{\mu C41}$), high mean time between failures to lose the positioning accuracy importance weight ($\omega_{\mu C42}$) and high mean time between failures to lose the volumetric accuracy

importance weight ($\omega_{\mu C63}$). Reliability index(C_4) can be evaluated by equation (4):

$$C_4= (\mu_{C41}{}^* \omega_{\mu C41})+(\mu_{C42}{}^* \omega_{\mu C42})+(\mu_{C43}{}^* \omega_{\mu C43}) \tag{4}$$

In case of small-to-medium size machine tool remanufacturing, equation (4) is simplified into:

$$C_4=0.5\ \mu_{C41}+ 0.4\ \mu_{C42}+ 0.1\ \mu_{C43}$$

Where:

$\omega_{\mu C41}$=0.5, $\omega_{\mu C42}$=0.4, $\omega_{\mu C43}$=0.1,
μ_{C41}: performance of remanufacturing to satisfy high mean time between failures to lose the geometric accuracy,
$\omega_{\mu C41}$: high mean time between failures to lose the geometric accuracy importance weight,
μ_{C42}: performance of remanufacturing to satisfy high mean time between failures to lose the positioning accuracy,
$\omega_{\mu C42}$: high mean time between failures to lose the positioning accuracy importance weight,
μ_{C43}: performance of remanufacturing to satisfy high mean time between failures to lose the volumetric accuracy,
$\omega_{\mu C43}$: high mean time between failures to lose the volumetric accuracy importance weight.

2.1.5 Processing range and efficiency index (C_5)

Remanufacturing conventional into CNC machine tool can improve the processing range and efficiency and reduce the time for machining the same products, where increased cutting feed rates and spindle speeds by into CNC remanufacturing, consequently can decrease the processing time considerably and increase the accuracy, in-shape-complexity and surface finish. Processing range and efficiency of remanufactured shaping into CNC machine tool can be expanded by increasing the number of controlled axes between 2 to 5 but with an increase in cost. Processing range and efficiency index can be divided into components of remanufacturing into single axis shaping machine tool (μ_{C61}), remanufacturing into 2-axis CNC shaping machine tool (μ_{C62}), remanufacturing into 3-axis CNC shaping machine tool (μ_{C63}), remanufacturing into 4-axis CNC shaping machine tool (μ_{C64}) and remanufacturing into 5-axis CNC shaping machine tool (μ_{C65}). Reassembly aided remanufacturing performance to provide flexible processing range and efficiency of shaping machine tool can be divided into five grades

include excellent, good, average, fair and poor with the corresponding values of 0.2, 0.4 , 0.6, 0.8 and 1 respectively. Processing range and efficiency components importance weights include remanufacturing into single shaping machine tool importance weight ($\omega_{\mu C61}$), remanufacturing into 2-axis CNC shaping machine tool importance weight ($\omega_{\mu C52}$), remanufacturing into 3-axis CNC shaping machine tool importance ($\omega_{\mu C53}$), remanufacturing into 4-axis CNC shaping machine tool importance ($\omega_{\mu C54}$) and remanufacturing into 5-axis CNC shaping machine tool importance ($\omega_{\mu C55}$). Processing range and efficiency index (C_5) can be calculated by using equation (5).

If 2= C_{5RCNC} / C_{5RC} <6 , then C_5>=0.6 so that μ_{C51}=0.8 , μ_{C52}=0.8 , μ_{C53}=0.6-0.8, μ_{C54}=0.6-0.8, μ_{C55}=0.6

If 1 = C_{5RC} / C_{5CNC} <2 , then C_5<0.6 so that μ_{C51}=0.95 , μ_{C52}=0, μ_{C53}=0, μ_{C54}=0, μ_{C55}=0

$$C_5= (\mu_{C51}{}^* \omega_{\mu C51})+(\mu_{C52}{}^* \omega_{\mu C52})+(\mu_{C53}{}^* \omega_{\mu C53})+ (\mu_{C54}{}^* \omega_{\mu C54})+ (\mu_{C55}{}^* \omega_{\mu C55}) \tag{5}$$

In case of small-to-medium size machine tool remanufacturing, equation (5) is simplified into:

$$C_5= (0.1\mu_{C51})+(0.2\mu_{C52})+(0.2\mu_{C53})+ (0.2\mu_{C54})+ (0.3\mu_{C55})$$

Where:

$\omega_{\mu C51}$=0.1, $\omega_{\mu C52}$=0.2, $\omega_{\mu C53}$=0.2, $\omega_{\mu C54}$=0.2, $\omega_{\mu C55}$=0.3,
C_{5RCNC}: conventional shaping into CNC machine tool remanufacturing processing range and efficiency,
C_{5RC}: conventional shaping into conventional machine tool remanufacturing processing range and efficiency,
μ_{C51}: performance of remanufacturing into single axis shaping machine tool,
$\omega_{\mu C51}$: remanufacturing into single shaping machine tool importance weight,
μ_{C52}: performance of remanufacturing into 2-axis CNC shaping machine tool,
$\omega_{\mu C52}$: remanufacturing into 2-axis CNC shaping machine tool importance weight,
μ_{C53}: performance of remanufacturing into 3-axis CNC shaping machine tool,
$\omega_{\mu C53}$: remanufacturing into 3-axis CNC shaping machine tool importance weight,
μ_{C54}: performance of remanufacturing into 4-axis CNC shaping machine tool,

$\omega_{\mu C54}$: remanufacturing into 4-axis CNC shaping machine tool importance weight,

μ_{C55}: performance of remanufacturing into 5-axis CNC shaping machine tool,

$\omega_{\mu C55}$: remanufacturing into 5-axis CNC shaping machine tool importance weight.

2.1.6 Ergonomic index (C_6)

Ergonomic evaluation of shaping into CNC machine tool remanufacturing can be evaluated by using the measures of ergonomic index (C_6) which can be divided into performance to provide high human-machine interaction (μ_{C61}), reassembly aided remanufacturing performance to provide high safety (μ_{C62}) and performance to provide high maintainability (μ_{C63}). Performance of ergonomic can be divided into five grades include excellent, good, average, fair and poor with the corresponding values of 0.2, 0.4 , 0.6, 0.8 and 1 respectively. Reassembly aided remanufacturing to provide high effective ergonomic, ergonomic components importance weights should include human-machine interaction importance weight ($\omega_{\mu C61}$), safety importance weight ($\omega_{\mu C62}$) and maintainability importance weight ($\omega_{\mu C63}$). Ergonomic index (C_6) can be evaluated by equation (6):

$$C_6=(\mu_{C61}* \omega_{\mu C61})+(\mu_{C62}* \omega_{\mu C62})+(\mu_{C63}* \omega_{\mu C63})$$
(6)

In case of small-to-medium size machine tool remanufacturing, equation (6) is simplified into:

$$C_6=0.4\mu_{C61} + 0.3\mu_{C62} + 0.3\mu_{C63}$$

Where:

$\omega_{\mu C61}$=0.4, $\omega_{\mu C62}$=0.3, $\omega_{\mu C63}$=0.3,

μ_{C61}: performance to provide high human-machine interaction,

$\omega_{\mu C61}$: human-machine interaction importance weight,

μ_{C62}: performance to provide high safety,

$\omega_{\mu C62}$: safety importance weight,

μ_{C63}: performance to provide high maintainability,

$\omega_{\mu C63}$: maintainability importance weight.

2.2 Alternatives Description

2.2.1 A_1: Conventional into conventional shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into conventional machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Reassembly,
5- Processing range and efficiency testing.

2.2.2 A_2: Conventional into 2-axis CNC shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 2-axis CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,
6- Introduction of servo motors to x-axis and tool slide based automated z-axis,
7- Introduction of CNC control cabinet and servo drivers to drive the servo motors of x and z axes,
8- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,
9- Reassembly,
10- Processing range and efficiency testing.

2.2.3 A_3: Conventional into 3-axis,three linear axes, CNC shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 3-axis, three linear axes, CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,
6- Introduction of ball screwed y-axis to machine table,
7- Introduction of servo motors to x-axis, y-axis and tool slide based automated z-axis,
8- Introduction of CNC control cabinet and servo drivers to drive the servo motors of x, y and z axes,
9- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,

10- Reassembly,
11- Processing range and efficiency testing.

2.2.4 A_4: Conventional into 3-axis, two linear and one rotary, CNC shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 3-axis, two linear and one rotary, CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,
6- Introduction of rotary A-axis to machine table,
7- Introduction of servo motors to x-axis, tool slide based automated z-axis and rotary A-axis,
8- Introduction of CNC control cabinet and servo drivers to drive the servo motors x, z and A axes,
9- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,
10- Reassembly,
11- Processing range and efficiency testing.

2.2.5 A_5: Conventional into 4-axis, three linear and one rotary, CNC shaping tool machine remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 4-axis, three linear and one rotary, CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,
6- Introduction of ball screwed y-axis to machine table,
7- Introduction of rotary A-axis to machine table,
8- Introduction of servo motors to x-axis, y-axis and tool slide based automated z-axis and rotary A-axis,

9- Introduction of CNC control cabinet and servo drivers to drive the servo motors of x, y, z and A axes,
10- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,
11- Reassembly,
12- Processing range and efficiency testing.

2.2.6 A_6: Conventional into 4-axis, two linear, one rotary and one tilting, CNC shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 4-axis, two linear, one rotary and one tilting, CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,
6- Introduction of integrated rotary A-axis and tilting B-axis to machine table,
7- Introduction of servo motors to x-axis, tool slide based automated z-axis and integrated rotary A-axis and tilting B-axis,
8- Introduction of CNC control cabinet and servo drivers to drive the servo motors x, z, A and B axes,
9- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,
10- Reassembly,
11- Processing range and efficiency testing.

2.2.7 A_7: Conventional into 5-axis, three linear, one rotary and one tilting, CNC shaping machine tool remanufacturing alternative

Alternative portfolio for remanufacturing conventional shaping into 5-axis, three linear, one rotary and one tilting, CNC machine tool contains the activities of:

1- Disassembly,
2- Cleaning,
3- Replace worn parts,
4- Introduction of ball screw to machine x-axis,
5- Introduction of ball screw to machine tool slide to develop automated z-axis,

6- Introduction of ball screwed y-axis to machine table,
7- Introduction of integrated rotary A-axis and tilting B-axis to machine table,
8- Introduction of servo motors to x-axis, y-axis, tool slide based automated z-axis and integrated rotary A-axis and tilting B-axis,
9- Introduction of CNC control cabinet and servo drivers to drive the servo motors of x,y,z,A and B axes,
10- Introduction of rotational speed inverter to control main motor to specify the stroke frequency,
11- Reassembly,
12- Processing range and efficiency testing.

2.3 Assessment Matrix

Assessment matrix can be constructed according to the following assumptions [1-4,6,9-15]:
Given:

A set of alternatives:

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

A set of criteria:

$C:\{C_1,C_2,C3,\ldots,Cn\}$

A set of performances:

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

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

$$P=A_W*C_W \tag{7}$$

Where:

P= alternative performance score,
A_W= alternative performance weight,
C_W= criteria importance weight,
$i=(1,2,3,\ldots,m)$
$j=(1,2,3,\ldots,k)$

Assessment constraints:

1- As high as the number of automated axes as high as the cost effectiveness to get accurate complex shape,
2- As high as the number of automated axes as high as the time effectiveness to get accurate complex shape,
3- As high as the number of automated axes as high as the accuracy and complex shape effectiveness to get accurate complex shape,

4- As high as the number of automated axes as high as the reliability effectiveness to get accurate complex shape,
5- As high as the number of automated axes as high as the processing range and efficiency effectiveness to get accurate complex shape,
6- As high as the number of automated axes as high as the ergonomic effectiveness to get accurate complex shape.

3. RESULTS AND DISCUSSION

The problem is a decision making to rank seven different alternatives which vary among conventional shaping to conventional machine tool remanufacturing to conventional shaping to 5-axis CNC machine tool remanufacturing which require integrated solution by considering all the criteria simultaneously to develop the performance determination of the alternatives and the criteria. To achieve the maximum comprehensive benefits of machine tool remanufacturing, impacts on the function, performance, quality, reliability and characteristics of remanufactured machine tools should be modeled and these factors should be developed into criteria. Since machine tools large sized structure casts include the main mechanical structure, related components and parts which have the characteristics of not changed much for a long time, long term natural aging, eliminated residual stress, higher precision stability, higher remanufacturing rate and certain technical feasibility. Remanufacturability assessment is divided into three interconnected sub-assessments to help improve performance to develop high added value at a relatively low cost where these sub-assessments include [12]:

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

Comparative literature analysis [1-12] and machine tool remanufacturing experience analysis were used to conclude the assessment matrix as show in Table 1. Alternatives take the order $A_7<A_6<A_5<A_4<A_3<A_2<A_1$ according to their ranks. Variation curve of ranks with alternative normalized weight of conventional shaping into CNC machine tool remanufacturing is illustrated in Fig. 4. Alternative normalized weight is calculated by using equation (8) by multiplying the summation of performances of an alternative

Table 1. Alternatives performance assessment matrix

| Index	Performance (A_1)	Performance (A_2)	Performance (A_3)	performance (A_4)	performance (A_5)	performance (A_6)	performance (A_7)
Cost(C_1)	0.68	0.70	0.72	0.74	0.81	0.88	0.95
Time(C_2)	0.68	0.70	0.77	0.84	0.86	0.88	0.95
Accuracy and complex shape(C_3)	0.50	0.60	0.70	0.76	0.80	0.90	0.96
Reliability (C_4)	0.50	0.60	0.70	0.80	0.90	0.98	0.98
Processing range and efficiency (C_5)	0.08	0.24	0.36	0.40	0.52	0.56	0.74
Ergonomic (C_6)	0.52	0.60	0.68	0.68	0.76	0.76	0.76
Summation of Performances (ΣA_n)	2.96	3.44	3.93	4.22	4.65	4.96	5.34
Alternative importance Weight (AIW)	0.02	0.04	0.06	0.08	0.08	0.08	0.1
Normalized Weight(NW)	0.06	0.14	0.24	0.34	0.37	0.40	0.53
Technical feasibility index	<0.6	0.68	0.76	0.83	0.91	0.91	0.99
Economic feasibility index	<0.6	0.68	0.76	0.83	0.91	0.91	0.99
Resource and environmental benefits index	<0.7	0.78	0.86	0.93	0.93	0.93	0.93
Rank	7	6	5	4	3	2	1
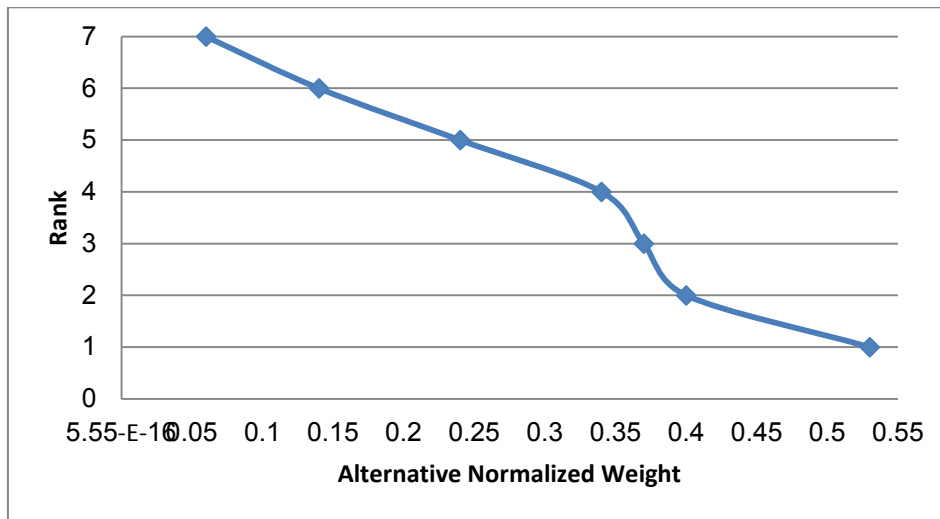
Fig. 4. Variation curve of ranks with alternative normalized weight of conventional shaping into CNC machine tool remanufacturing
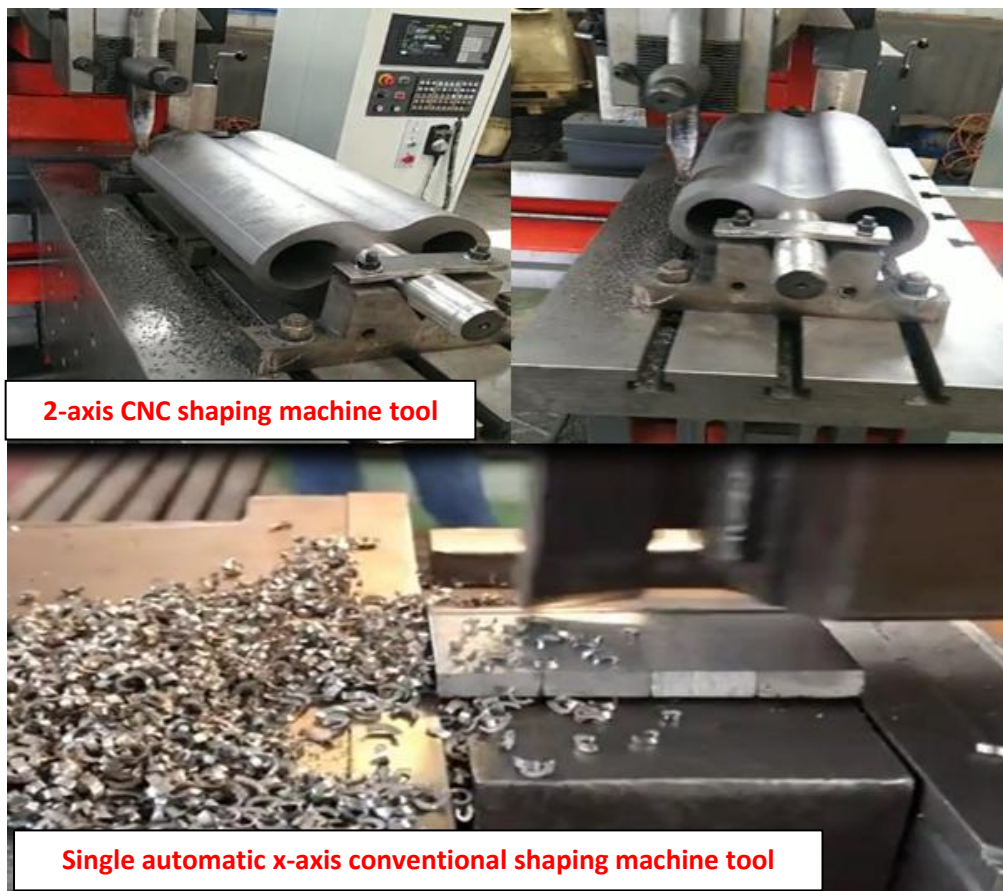

Fig. 5. 2-axis CNC shaping machine vs single automatic x-axis conventional shaping machine

against all criteria by alternative importance weight, which is experience based evaluated measure as shown in Table 1. Linear regression was applied to the plotting of summation of performances to get the value of (Δ=0.078) as a descending value of technical feasibility, economic feasibility and resource and environmental benefits with reduction the number

of CNC automated axes as show in Table 1. Remanufacturability index of conventional shaping into CNC machine tool remanufacturing is of the value of (RI=0.97) according to linear regression procedure. Using emerged cheap CNC technology will convert the remanufacturing paradigm to dominate cost and time effectiveness of conventional shaping into CNC machine tool reassembly aided remanufacturing over conventional shaping into conventional machine tool remanufacturing. By comparing conventional shaping into 2-axis CNC machine tool with single automatic x-axis conventional shaping machine tool , it is obvious to recognize the dramatic change in shaping machine tool performance where very high enhancement can be obtained regard all of accuracy and complex shape, reliability and processing range and efficiency as show in Fig. 5. The shaping machine is remanufactured into independent machine tool to produce finished by-product instead of primary billets fit-to-size or surface cleaning by-process machine tool.

$$NW = \Sigma An *AIW \qquad (8)$$

Where:

NW= normalized weight,
ΣAn = alternative performance weight,
AIW= summation of performances.

4. CONCLUSION

Conclusions include:

- Conventional shaping into CNC machine tool remanufacturability value can reach the value of (RI=0.97) on scale of the closed interval [0,1],
- Technical feasibility index of remanufactured conventional shaping into CNC machine tool is over the threshold of 0.6 according to [9] to be of the values [0.68, 0.76, 0.83, 0.91, 0.99], Table 1,where increasing the number of automated axes of remanufactured CNC shaping machine tool increases the technical feasibility,
- Economic feasibility index of remanufactured conventional shaping into CNC machine tool is over the threshold of 0.6 according to [9] to be of the values [0.68, 0.76, 0.83, 0.91, 0.99], Table 1,where increasing the number of automated axes of remanufactured CNC

shaping machine tool increases the economic feasibility.
- Resource and environmental benefits index of remanufactured conventional shaping into CNC machine tool is over the threshold of 0.7 according to [9] to be of the values [0.78, 0.86, 0.93], Table 1, where increasing the number of automated axes of remanufactured CNC shaping machine tool increases the resource and environmental benefits feasibility,
- Large remanufacturing value and high technical content lead to high value added of conventional shaping into CNC machine tool,
- Implementation and benefits of conventional shaping into CNC machine tool remanufacturing are directly affected function by various configuration alternative according to the number of automated axes solutions,
- For various stakeholders, educational institutions and small to medium investors, simple configuration machine tools can obtain better comprehensive benefits and reduce the potential risk of remanufacturing.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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