



Conventional milling into CNC machine tool remanufacturing: Sustainability modeling

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Article history:

Received: July 25, 2020

1st Revision: August 25, 2020

Accepted: October 30, 2020

JEL classification:

Q56

L64

O14

DOI:

[10.14254/jems.2020.5-2.3](https://doi.org/10.14254/jems.2020.5-2.3)

Abstract: **Aims:** Sustainability modeling for conventional milling into CNC machine tool remanufacturing-upgrading. **Study design:** Remanufacturing-upgrading of conventional milling into CNC machine in its mechanical part, it is merely traditional remanufacturing process of conventional milling where gearbox can be eliminated due to use of motorized axes. Lead screws can be replaced with motorized ball screws. Heavy parts of machine bed such column, knee and saddle are reused. A group of criteria are selected to conduct comprehensive sustainability assessment of remanufacturing-upgrading process include: 1. Remanufacturing cost: It is the cost of milling remanufacturing into CNC machine. 2. Remanufacturing time: It is the duration of time required for milling remanufacturing into CNC machine. 3. Accuracy: It is an expected technical performance of remanufactured milling into CNC machine. 4. Reliability: It is an expected technical performance of remanufactured milling into CNC machine. 5. Processing efficiency: It is the man-hour based productivity efficiency of a remanufactured milling into CNC machine. 6. Processing range: It is the flexibility of remanufactured machine tool into CNC machine. 7. Ergonomics: It is the interaction among operator, remanufactured milling into CNC machine tool and other system unit through the cell of manufacturing. Conventional machine tool into CNC machine remanufacturing-upgrading experience is used to project the suitable literature comparatively to construct sustainability assessment model. Sustainability assessment models in field of remanufacturing-upgrading are reviewed and modified to accommodate new changes that accompany the current case study.



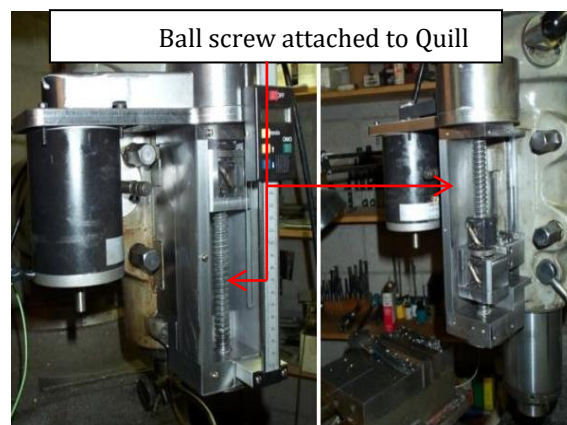
Place and Duration of Study: Middle Technical University, Institute of Technology-Baghdad, Mechanical Techniques Department, between February 2020 and July 2020. **Methodology:** Literature survey in area of remanufacturing assessment and remanufacturing sustainability assessment. Comparative literature based assessment application. Classification of literature sample. Re-representation of discussions and conclusions. Graphical representation of results. Isolation of criteria. Case study definition. Weighting of criteria. Triangular fuzzification of criteria. Weighting of satisfaction. Global weights calculation. Sustainability Index weight calculation. **Results:** Summation of sub-sustainabilities index weights is within limit of consistency. Environmental sustainability literature is predominated to be followed by economic and technical sustainabilities literature. **Conclusion:** Economic, environmental and social sub-sustainabilities are of good performances and directed toward sustainability. Social and management sustainability are interlinked and require more studies to be directed toward sustainability.

Keywords: remanufacturing sustainability modeling, conventional milling remanufacturing, remanufacturing-upgrading sustainability, CNC machine tool remanufacturing, CNC conversion kit sustainability.

1. Introduction

Vertical knee milling machine can be analyzed to study sustainability based remanufacturability. Eco-redesign potentials of remanufacturing-upgrading of conventional milling machine into CNC machine tool can include:

Figure 1: Linear actuator to quill based Z-axis movement



Source: Hugh Currin (n.d.)

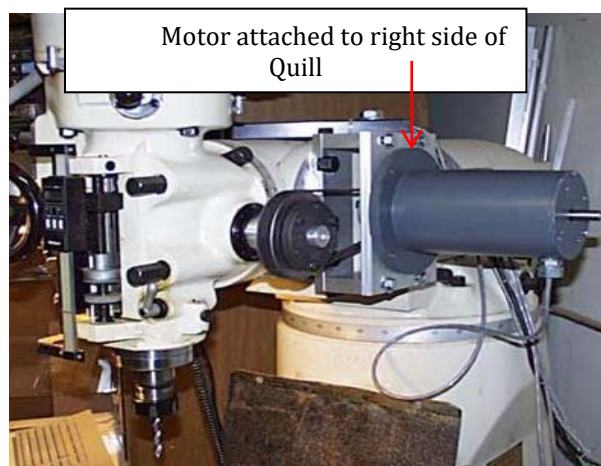
1- Linear Actuator based Quill Movement based Z-axis

Starting with Figure 1 which shows a vertical knee milling machine that remanufactured-upgraded by (Liu et al., 2019), modified configuration includes:-

- 1- Servo motors are attached to X-axis and Y-axis.
- 2- Ball screw and Z-axis servo motor are attached with quill to enable linear motion. Using of ball screw is a source of accuracy while inaccuracy can arise due mechanism of ball screws ends and of ball screw nut to quill connections. Such mechanism is predominated to upgrade the vertical knee milling machine.
- 3- Mounts of servo motors are sources of inaccuracy where rigidity plays an important role.
- 4- Using of pulleys or sprockets and belts or chains will be sources of inaccuracy so that servo planetary gearbox speed reducer is better to reduce backlash and remove mechanical hysteresis through direct connection among servo motor, gearbox and ball screw. Planetary gearbox reduction ratio should be defined to half closed CNC control system.
- 5- Z-axis travel is no more than 120mm in such upgrading approach.

2- Rotary Actuator Quill Movement based Z-axis

Figure 2: Rotary Actuator to Quill based Z-axis Movement, right side attachment



Source: Mumford Micro Systems (n.d.).

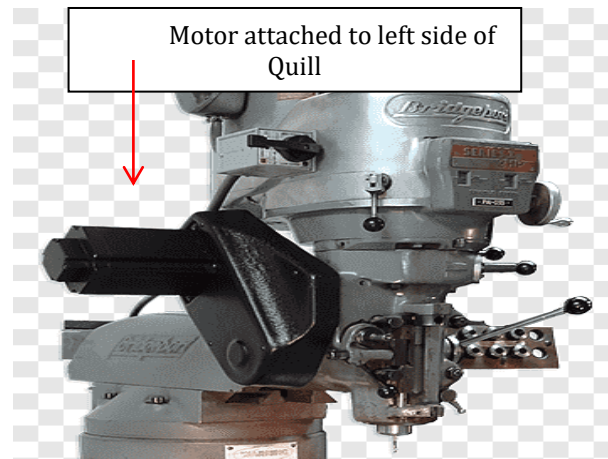
Z-axis servo motor can be attached with quill realizing handle to be to the right side of the machine head, Figure 2, to enable rotary actuator attachment. Using belt and pulleys is a source of inaccuracy, malfunction of quill handle and Z-axis travel is no more than 120mm in such upgrading approach. To keep function of quill handle, rotary actuator is attached to left side of head to be attached to quill handle rotary axis, Figure 3.

3- Rotary Actuator, Z-axis handle Position ,knee based Z-axis Movement

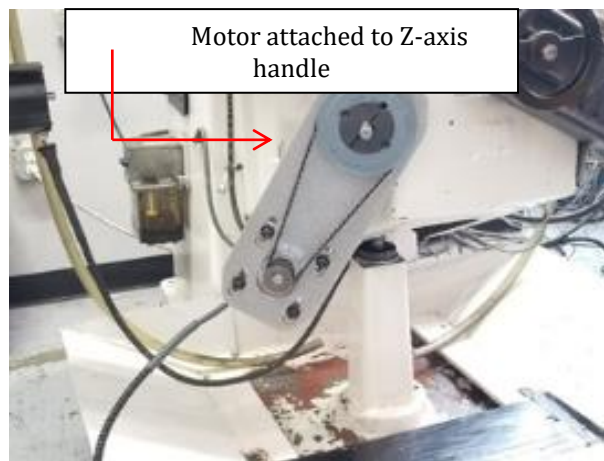
Z-axis servo motor can be attached with Z-axis handle which is located inside the knee, Figure 4, to enable upgrading. Z-axis travel is more than 300mm in such upgrading approach.

4- Rotary Actuator , Machine Base Position, knee based Z-axis Movement

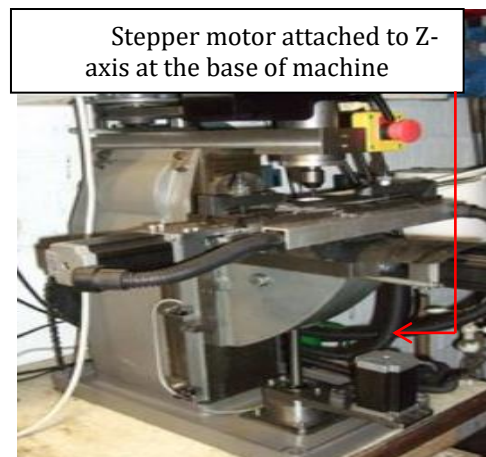
Z-axis servo motor can be attached with ball screw of z-axis directly which is located vertically through the knee, Figure 5, to enable upgrading. Z-axis travel is more than 300mm in such upgrading approach.

Figure 3: Rotary Actuator to Quill based Z-axis Movement, left side attachment

Source: PNGWING. (n.d.)

Figure 4: Linear Actuator to knee based Z-axis movement

Source: MicroKinetics Corporation (2020)

Figure 5: Linear Actuator to knee based Z-axis movement

Source: Pinterest (n.d.).

Provide a factual background, clearly defined problem, proposed solution, a brief literature survey and the scope and justification of the work done. Analysis of the industry development status

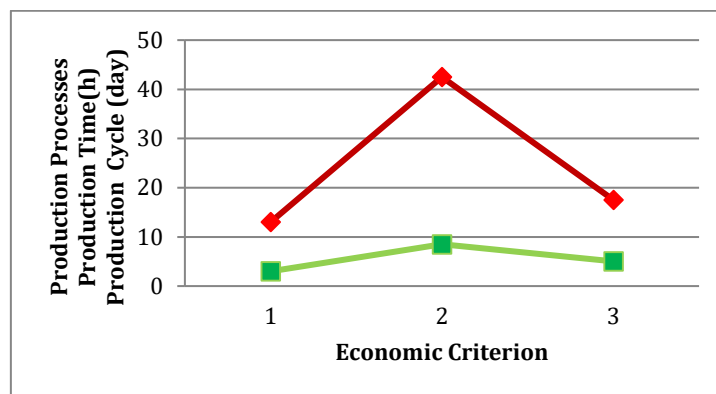
of machine tool remanufacturing points out that the machine tool remanufacturing industry is active due to interaction among (Du & Li, 2014):

- Original Equipment Manufacturers of machine tool: Because it is in brand, technology, talented persons and logistics so that the main body of machine tool remanufacturing industry.
- Third-party remanufacturers.
- Manufacturers of Numerical Control system.

Development characteristics of milling remanufacturing industry can be analyzed through various models of machine tool remanufacturing including:

- Recycling-based machine tool remanufacturing.
- Solution-based machine tool remanufacturing.
- Trade-in machine tool remanufacturing.
- Economic viability is satisfied where cost of remanufactured milling can be 40%-60% of the new one. Production processes, production time or production cycle represent production capacity which represent economic criteria. Production capacity based comparison between new and remanufactured machine tools can be show in the Figure 6.

Figure 6: Alternative based criterion weight variation



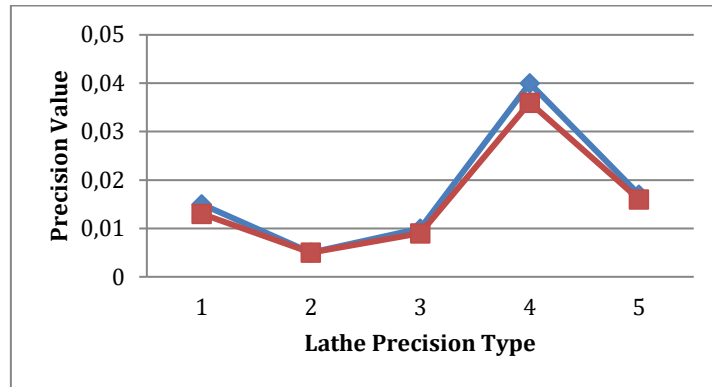
Red: new machine tool, Green: remanufactured machine tool (1): Production processes, (2): production time, (3): production cycle

Source: Du & Li (2014)

Technical viability is satisfied where the comparison of the precision between the remanufactured machine and the new one with standard parameters can be shown in figure 7. High restoration of precision values can be satisfied which mean high percentage of quality standard can be met.

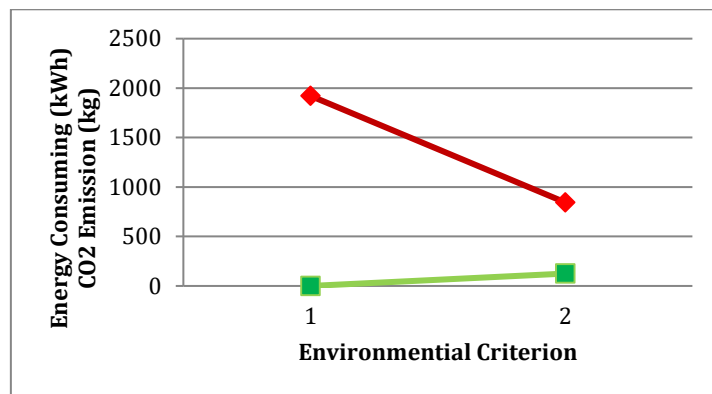
Environmental viability is satisfied where Remanufacturing-upgrading can improve the Milling efficiency by 10%-20% during operating. While reusing value-added parts can save more than 80% of power which required for manufacture new milling. Also greenhouse gases can be greatly reduced. Figure 8 can show environmental viability of machine tool remanufacturing-upgrading with taken in consideration the CO₂ emissions limits include the emissions generated from material and energy indirectly and the direct emission during remanufacturing. The carbon coefficient of cast iron is 1.91 kgCO₂/kg while the carbon coefficient of electricity is 0.785 kgCO₂/kWh.

Figure 7: Alternative based criterion weight variation



Blue: new machine tool, Red: remanufactured machine tool, (1): Radial straightness, (2): Periodic axial play, (3): pitch error, (4): Accumulated pitch error, (5): Helix slope error
 Source: Du & Li (2014)

Figure 8: Alternative based criterion weight variation



Red: new machine tool, Green: remanufactured machine tool (1), (2): production time, (3): production cycle
 Source: Du & Li (2014)

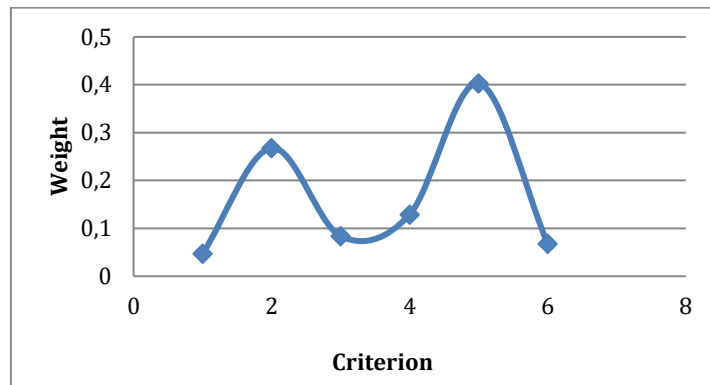
According to Abdullah et al. (2015; 2018), remanufacturing is sustainable development with economic, environmental and social viabilities with high potentials to be applied in large scale to develop triple-bottom lines sustainability to help emerge and dominate sustainable manufacturing to be a long term developing approach through closing the supply chain of production. By application of remanufacturing to upgrade conventional milling into CNC machine for educational and industrial training application, cost will be at its lower level and chance for resources sharing and facilities between education, training industry and remanufacturing industry can be obtained.

Environmental viability is also consistent where high flexibility are supported with further reduction of power and carbon emissions through using of CNC machines technology to eliminate worn dovetail guide ways which can lead to save high added-value parts of milling. Social viability will be satisfied based on economic and environmental viabilities where human employment, development and experience accumulation can be delivered through education, training and remanufacturing industry Du & Li (2014). Selection system criteria of decision-making requires informative multiple stakeholders data collection to integrate more criteria through comprehensive selection of benefits alternative. Informative assessment criteria weighting which based on literature surveying

Remanufacturing represents a business opportunity and in many cases a mean to promote environmental sustainability. A multi-criteria decision making modeling is required to help economically and effectively conventional milling into CNC machine remanufacturing. Multi-criteria decision making modeling can be used for selecting remanufacturing technology. Remanufacturing technology portfolios are fertile to be optimized concern benefits associated with each portfolio.

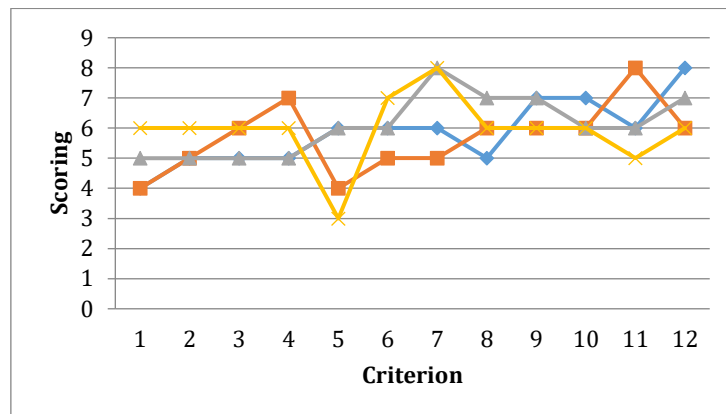
Multi-criteria modeling can include time , quality, cost and service as economic criteria and process emission and resource consumption which weight as show in Figure 9 (Jiang, Zhang & Sutherland, 2011).

Figure 9: Remanufacturing sustainability assessment criteria



(1): Time, (2): Quality, (3): Cost, (4): Service, (5): Process Emission, (6): Resource Consumption
 Source: Jiang, Zhang & Sutherland (2011)

Figure 10: Sustainability assessment of remanufactured milling as a remanufacturing technology comparing with CNC grinding



Blue, thermal spray; Red, arc welding; purple
 Source: Jiang, Zhang & Sutherland (2011)

By analyzing the curve in Figure 9, it is easily to point out that quality and process emission are of high weights criteria where quality is very required to continue the remanufacturing business through retained mechanical structure to its quality standard which lets accuracy, reliability , processing efficiency to be improved so that processing range increases and ergonomics satisfy operator. Since remanufacturing is proved sustainable development with concentration on environmental development to be environmental conscious industry, so process emission is of the highest weight criterion.

By applying ascending ordering, time is of the lowest weight of importance of criterion and it is divided into cycle time and remanufacturing time. Resource consumption can be divided into energy efficiency and amount of raw material consumption. Resource consumption is of greater weight than time and thus it is importer than it. Cost is more importance than time and Resource consumption which is the cost of equipment and tooling. Frequency of maintenance and frequency of training form criterion of service which is more importance than cost. Process emission is the amount of solid waste and amount of liquid waste and it is of the second highest weight of importance after quality which is of the highest weight of importance and it is divided into capability and reliability Figure 9.

Benefits can be gotten through subdividing of economic and environmental criteria to include evaluation sub-criterion of (1) Cycle time, (2) Remanufacturing time, (3) Capability, (4) Reliability,

(5) Equipment cost, (6) Tooling cost, (7) Frequency of maintenance, (8) Frequency of training, (9) Amount of solid waste, (10) Amount of liquid waste, (11) Energy efficiency and (12) Amount of raw material consumption. The pair-wise comparison approach of Analytic Hierarchy Process can be employed for remanufacturing technology portfolio selection. An illustrative example to lend insights into the application of decision making for remanufacturing technology portfolios selection is shown in Figure 10. Remanufactured machine tool into CNC machine represents a reasonable alternative as a remanufacturing technology, green curve in Figure 10, comparing with CNC grinding machine, thermal spray equipment and arc welding equipment.

Failures and faults that can be observed by sliding parts such as dovetail guide ways under conditions of heat, coolant, lubricants and material chip can include:

- 1- Wear which requires remanufacturing to be rectified to portfolio that includes thermal spraying or arc welding as additive operation to be followed by milling and grinding as machining operation.
- 2- Nicks and dents which require remanufacturing to be rectified to portfolio that includes thermal spraying or arc welding as additive operation to be followed by milling and grinding as machining operation.
- 3- Corrosion which requires remanufacturing to be rectified to portfolio that includes thermal spraying or arc welding as additive operation to be followed by milling and grinding as machining operation.

Remanufactured conventional milling into CNC machine can be used for rectifying wear, nicks and dents and corrosion by remanufacturing technology alternatives included:

- 1- Buy a new CNC grinding machine.
- 2- Remanufacturing-upgrading conventional milling into CNC machine of an existing milling.
- 3- Procure arc welding equipment.

The maximum total benefit can be achieved with the lowest-cost portfolio that include buy a new CNC grinding machine, upgrade turning capabilities of an existing milling and procure arc welding equipment, Figure 11. It is remanufacturing based manufacturing perspective which is better to upgrade the milling since such approach benefits both remanufacturing and manufacturing operations.

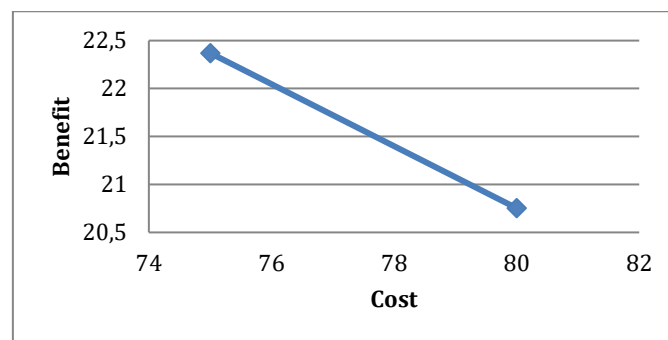
Wear, Nicks and dents and Corrosion can be rectified by using the following remanufacturing portfolio or remanufacturing technological path:-

- 1- Buy a new CNC grinding machine, Remanufacturing-upgrading conventional milling into CNC machine of an existing milling and Procure arc welding equipment.
- 2- Buy a new CNC grinding machine, Remanufacturing-upgrading conventional milling into CNC machine of an existing milling and Procure thermal spray equipment.

Remanufactured machine tool can help with arc welding technology in reduction the capital investment to start remanufacturing business of worn valves, Figure 10.

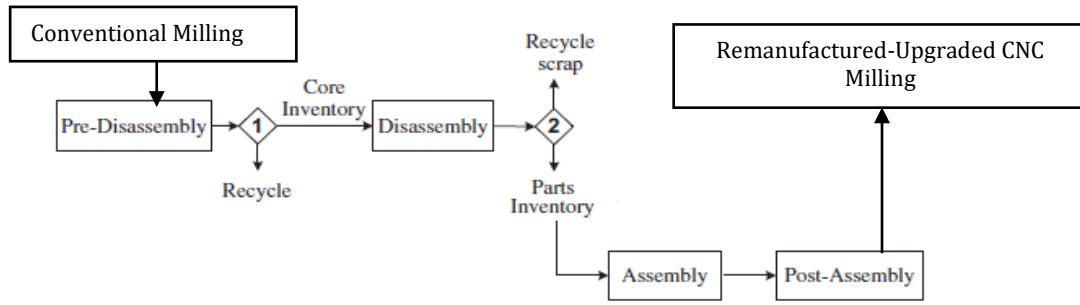
By applying comparative literature between Abdullah et al. (2018) and Jiang, Zhang & Sutherland (2011), disassembly-assembly oriented remanufacturing system can be emerged, Figure 12. Based on Abdullah et al. (2015), disassembly-assembly oriented remanufacturing system can enhance technical viability of remanufacturing-upgrading of CNC machine tool, Figure 14, comparing with remanufacturing system show by Jiang, Zhang & Sutherland (2011) in Figure 13.

Figure 11: Benefit-Cost of CNC grinding-remanufactured milling-arc welding as a remanufacturing technology comparing with CNC Grinding-remanufactured milling- thermal spray



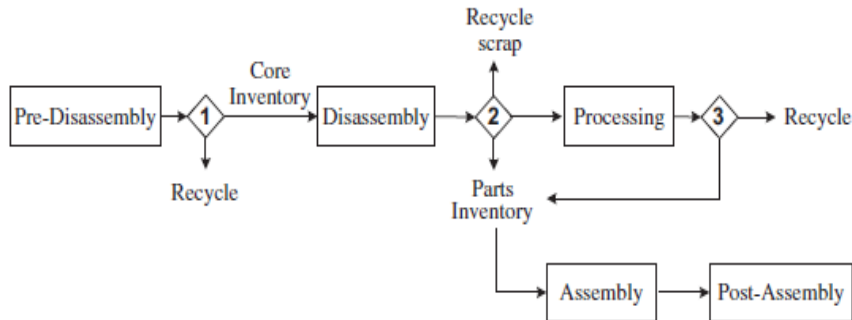
Source: Jiang, Zhang & Sutherland (2011)

Figure 12: Proposed assembly-disassembly oriented remanufacturing system



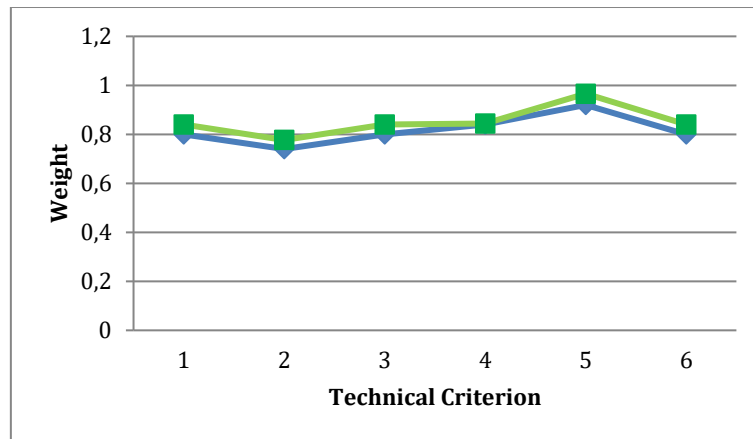
Source: Abdullah et al. (2018)

Figure 13: Conventional technology based remanufacturing system



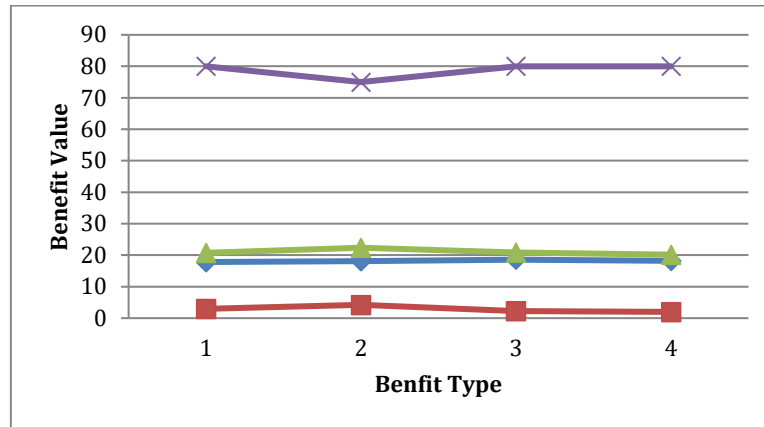
Source: Jiang, Zhang & Sutherland (2011)

Figure 14: Disassembly-assembly oriented remanufacturing system can enhance technical viability of remanufacturing-upgrading of CNC milling comparing with remanufacturing system



Source: Abdullah et al. (2018)

Synergistic effects consider the overall benefits of remanufacturing technology portfolio would be created that does not enterprise. Second portfolio is of the highest synergistic benefits so it is the most attractive solution comparing with the third portfolio which is of the highest singular benefits which highlights the significant of synergistic benefits. High synergistic benefits can be delivered with lowest cost of second portfolio. Figure 15 show how synergistic benefits, red curve, singular benefits, blue curve, total benefits, green curve, and cost, purple curve, vary with remanufacturing system portfolio (Jiang, Zhang & Sutherland, 2011).

Figure 15: Remanufacturing portfolio based benefit type analysis

(1): new CNC grinding-upgraded lathe into CNC-thermal spray, (2): new CNC grinding-upgraded lathe into CNC-arc welding, (3): new CNC grinding-thermal spray-arc welding, (4): upgraded lathe into CNC-thermal spray-arc welding

Source: Jiang, Zhang & Sutherland (2011)

Remanufacturing ecological performance evaluation methodology can be of configuration as shown in Figure 16. High level of customer satisfaction can be observed by reviewing Figure 17 which means that remanufactured products are of high acceptance. This can be certain with high (profit/cost) ratio as shown in Figure 18. Remanufacturing sustainability assessment can include criteria of Jiang, Ding, Zhang, Cai & Liu (2019):

- **Economic measure criteria include:**

- 1- Remanufacturing Cost can be divided into sub-criteria of cost can be divided into cost of purchasing of End-of-life millings, transportation cost, inventory cost, remanufacturing processing cost and cost of purchasing replace parts.
- 2- Remanufacturing Income can be divided into sub-criteria of remanufacturing profit, parts reuse income, waste disposal income, government incentive income, total asset utilization and net asset yield
- 3- Environmental protection fund investment can be classified into sub-criteria of environmental management investment, pollution control investment, and environmental rehabilitation investment.
- 4- Production input can be divided into sub-criteria of management service cost, logistics cost, cost of supplemental material, depreciation for plant assets, waste management cost.

- **Environment measure criteria include:**

- 1- Environmental benefit can be divided into sub-criteria of energy saving rate, comprehensive utilization rate of industrial wastewater, comprehensive utilization rate of industrial exhaust fumes, comprehensive utilization rate of industrial solid waste, the utilization rate of environmentally friendly materials and rate of remanufacturing for End-of-life products
- 2- Exhaust fumes emissions can be divided into sub-criteria of carbon dioxide (CO₂) emission, sulfur dioxide (SO₂) emission, compounds of nitrogen and oxygen emission.
- 3- Sewage discharge can be divided into sub-criteria of wastewater discharge and ammonia nitrogen emission
- 4- Waste discharge can be divided into sub-criteria of solid waste, non-recyclable waste resource and energy

- **Resource and energy measure criteria include:**

- 1- Original energy consumption can be divided into sub-criteria of coal consumption, crude oil consumption, natural gas consumption and water consumption.

- 2- Electrical energy consumption can be divided into sub-criteria of resource utilization rate of material reuse, rate of material recovery and other material resource consumption

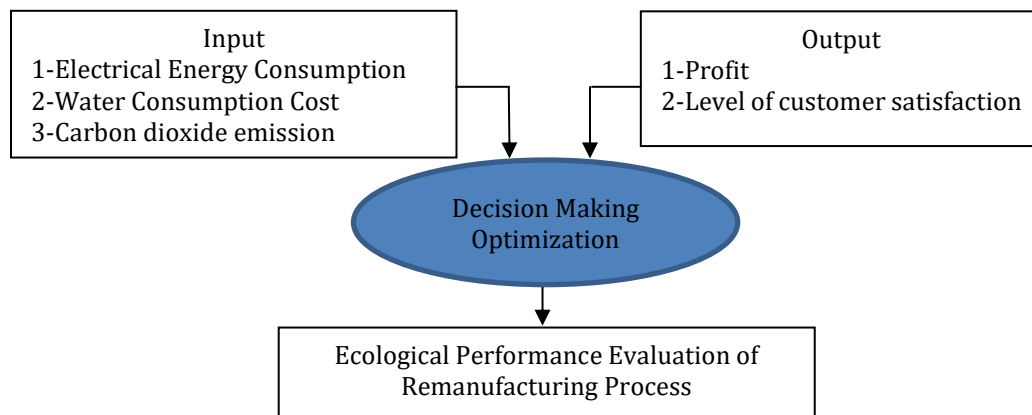
• **Society measure criteria include:**

- 1- Service level can be divided into sub-criteria of level of customer satisfaction in remanufacturing products, level of customer dissemination for remanufacturing information, level of remanufacturing quality management, market response time, recovery convenience and remanufacturing capacity
- 2- Social responsibility can be divided into sub-criteria of corporate green image, degree of cleaner production, meet emission standards, comply with the laws and regulations and market share of remanufacturing products.

Ecological performance evaluation criteria can include, Figure 19:

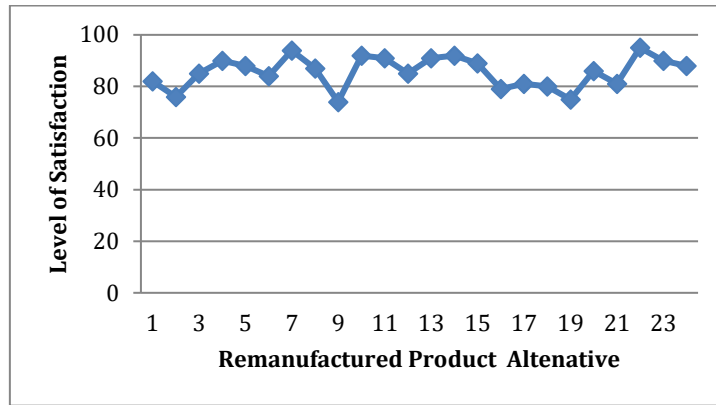
- 1- Material Resource Consumption.
- 2- Rate of Material Recovery.
- 3- Rate of Material Reuse.
- 4- Electrical Energy Consumption.
- 5- Rate of Remanufacturing for End-of-Life products.
- 6- The Utilization Rate of Environmentally friendly Materials.
- 7- Comprehensive Utilization Rate of Industrial Solid Waste.
- 8- Comprehensive Utilization Rate of Industrial exhaust Fumes.
- 9- Comprehensive Utilization Rate of Industrial Wastewater.
- 10- Energy-saving Rate
- 11- Cost of Purchasing Replace Parts.
- 12- Remanufacturing Processing Cost.
- 13- Inventory Cost.
- 14- Transportation Cost.
- 15- Cost of Purchasing End-of-Life Products.

Figure 16: Evaluation methodology of Ecological performance of remanufacturing



Source: Jiang, Ding, Zhang, Cai & Liu (2019)

Figure 17: Remanufactured product alternative based level of satisfaction assessment



Source: Jiang, Ding, Zhang, Cai & Liu (2019)

Material Resource Consumption, Electrical Energy Consumption, The Utilization Rate of Environmentally friendly Materials and Cost of Purchasing Replace Parts criteria weight are the highest. Mate/Insert/Bolt based emerged CNC technology based assembly can certain reduction of cost of purchasing replace parts, material resource consumption and electrical energy consumption. The utilization rate of environmentally friendly Materials can be enhanced relatively since all new part will not be manufacturing locally and assembly process will be energy-free. Remanufacturing ecological performance evaluation is of great significance for realizing the economic and environmental benefits. Different techniques can be used to model the remanufacturing ecological performance which includes:

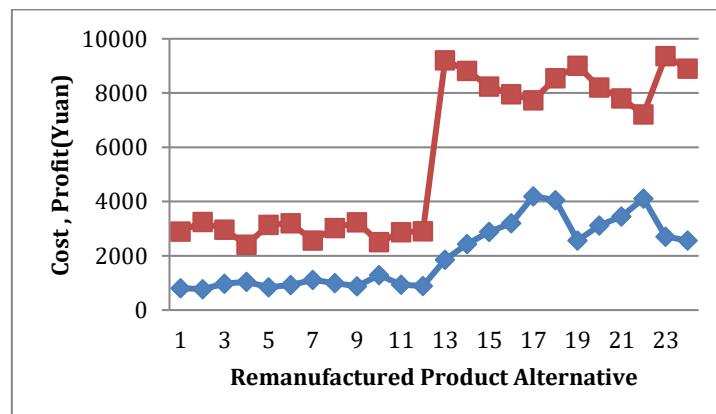
- Data driven Modeling.
- Qualitative Evaluation.
- Data Envelopment Analysis.

Evaluation techniques can suffer from, with keep in mind big data technology can be utilized to increase the objectivity and universality of the results and enhance the accuracy of the analysis:-

- Some criteria have uncertain effect on the results.
- Generalizability of the findings is constrained.

Clustering techniques can be used to select indicators and avoid subjective results generated by random indicators selecting. Ecological performance and remanufactured public acceptability based remanufacturing technology optimization is an effective measures. Energy-saving rate, remanufacturing process cost and rate of remanufacturing are key drivers impacting the remanufacturing ecological performance.

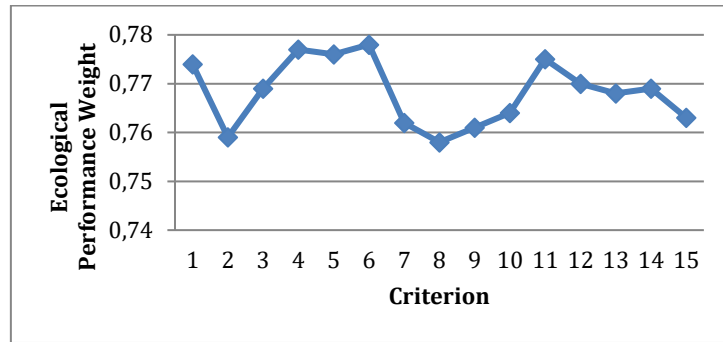
Figure 18: Remanufactured product alternatives based cost-profit assessment



Blue: cost, Red: Profit

Source: Jiang, Ding, Zhang, Cai & Liu (2019)

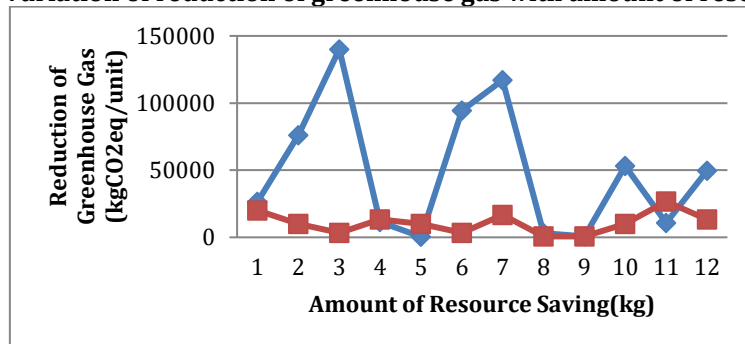
Figure 19: Ecological remanufacturing performance assessment criteria



Source: Jiang, Ding, Zhang, Cai & Liu (2019)

Economic efficiency and environmental effects of introducing remanufacturing of construction machinery can be analyzed by life cycle assessment in terms of resource saving and greenhouse gas reduction. Economic value can be certain by remanufacturing of major parts of equipment and machinery can generate added-value of 15 billion annually. Environment value can be measured as 4,415 tons of resource saving which can be of highest percentage of 63% and 224 thousand tons of greenhouse gas reduction, figure 20. Even remanufactured quantity is low but if the unit price of remanufactured is high, this will which show high economic effect. Economic and environmental effects of revitalization based remanufacturing can expand remanufacturing market (Jun et al., 2020).

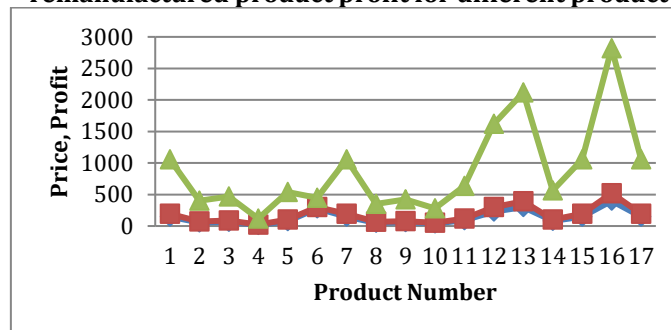
Figure 20: Variation of reduction of greenhouse gas with amount of resource saving



Source: Jun et al. (2020)

Contents based analysis and comparative literature based analysis economical effect is the difference in price between used and remanufactured equipment. Environmental effect can be obtained by life cycle assessment. Variation in price of reused and remanufactured equipment and machinery and the profit can be gathering by remanufacturing can be shown in Figure 21.

Figure 21: Variation of remanufactured product price, reused product price and remanufactured product profit for different product

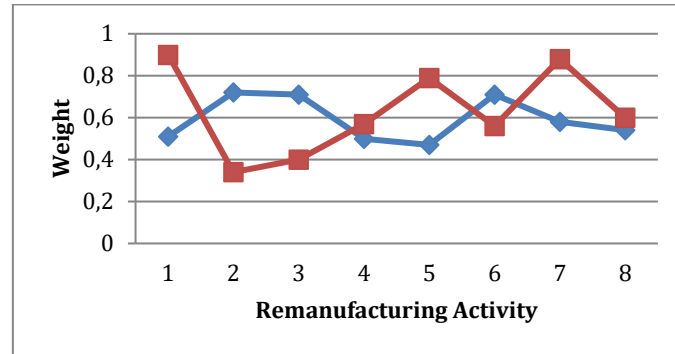


Blue: reused product price, Red: remanufactured product price, Green: remanufactured product profit

Source: Jun et al. (2020)

Re-manufacturability can be assessed by weighting the following activities of remanufacturing which include inspection and sorting, cleaning, disassembly, diagnostic testing, repair and upgrade, reassembly, functional test and final restoration and inspection. An example of two remanufactured products (A) and (B) are used to illustrate the variation of activity satisfaction which is based on product design, returned availability, fault statute, required time and level of technical expertise required to achieve the remanufacturing activity Figure 22.

Figure 22: Remanufacturing activities satisfaction weight variation



Blue: Product A, Red: Product B

Source: Omwando et al. (2018)

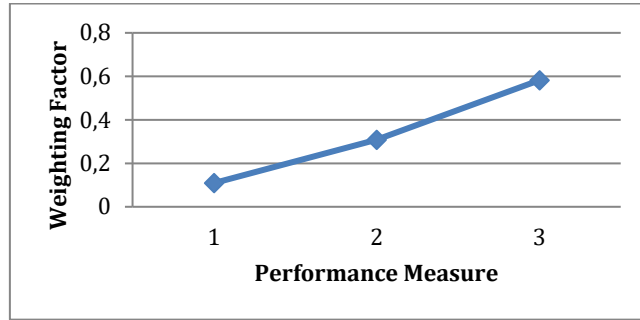
Product (A) is of higher remanufacturability index of (0.662) due to larger in size, period of trading in the market and higher percentage of billable returns and thus not relatively labor restrictive. Product (B) is of lower remanufacturability index of (0.448) due to relatively of small size, has been in the market for less than five years and higher proportion of returns under warranty and thus labor restrictive. Families of products can be compared to aid making tactical decisions regarding remanufacturing activity based satisfaction analysis. According to Industry experts based expectation, remanufacturing activity can take between 80% and 120% of the time (t) that it can be taken to manufacture new product according to remanufacturing activity index (Omwando et al., 2018):

If $t_{\text{remanufacturing}} > 120\% t_{\text{manufacturing}}$, the remanufacturing activity is unfavorable.

If $t_{\text{remanufacturing}} < 80\% t_{\text{manufacturing}}$, the remanufacturing activity is favorable.

Resource depletion potential, global warming potential, respiratory inorganics, acidification potential and water eutrophication potential can be criteria to assess environmental impact measure. Processing cost criterion can be used to assess economic viability measure. Bonding strength, substrate deformation, hardness and porosity criteria can be used to assess technological viability measure. Remanufacturing portfolio performance or remanufacturability can be assessed by using measures of environmental impact, economic viability and technological viability which are of different weights as show in Figure 23. Global weights and local weights of criteria which can be used for assessing environmental impact and technical viability of remanufacturing portfolio alternatives are show in Figures 24 and 25. Laser cladding, plasma arc surfacing, brushing electroplating and plasma spray are remanufacturing portfolio alternatives. Euclidian distance from each alternative to the ideal solution and the negative ideal solution can be determined to find relative closeness of each alternative to the ideal solution. As big as the difference between distances, as big as the relative closeness so that the highest rank can be obtain by an alternative. Euclidian distances and relative closeness of remanufacturing portfolio alternatives of laser cladding, plasma arc surfacing, brushing electroplating and plasma spray and the result show that brushing electroplating rank the first as an additive remanufacturing technology Figure 26 (Peng, et al., 2019).

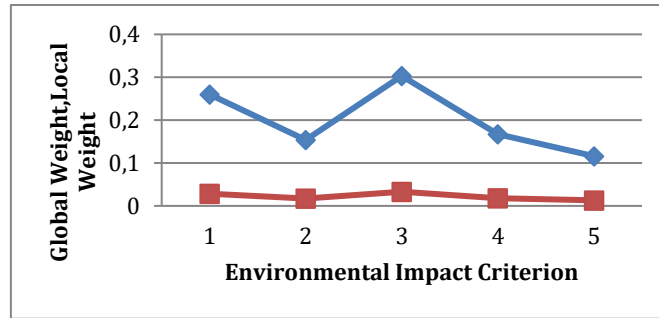
Figure 23: Remanufacturing sustainability assessing measures



(1): Environmental impact Measure, (2): Economic viability measure, (3): technological viability measure

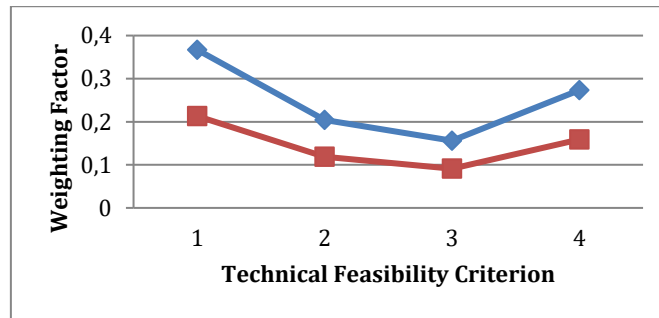
Source: Peng, et al. (2019)

Figure 24: Variation of global and local weights of environmental impact criteria



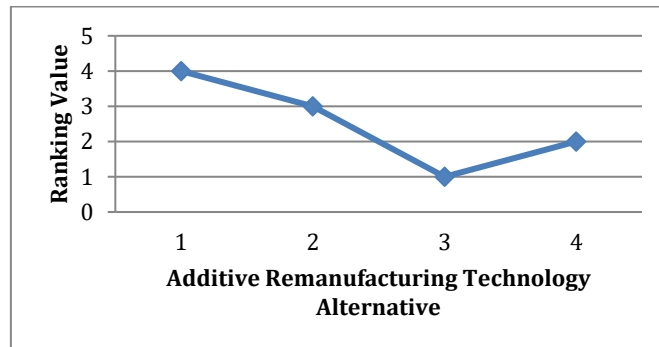
Source: Peng, et al. (2019)

Figure 25: Variation of global and local weights of technical viability criteria



Source: Peng et al. (2019)

Figure 26: Ranks of additive remanufacturing portfolio alternatives



(1): Laser Cladding, (2): Plasma Arc Surfacing, (3): Brushing electroplating, (4): Plasma spray

Source: Peng et al. (2019)

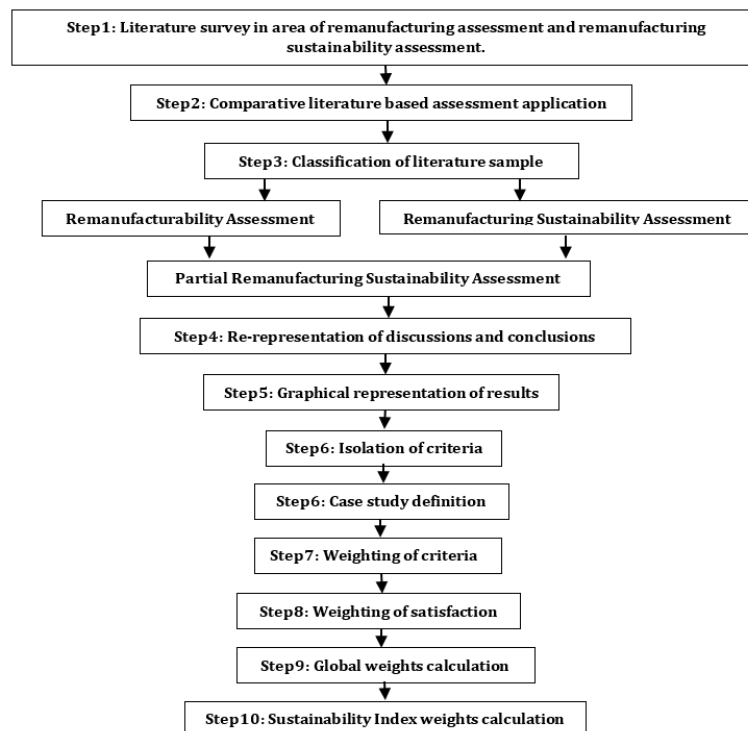
2. Sustainability assessment methodology

Methodology to apply comparative literature based analysis of remanufacturing assessment includes the following steps:

- 1- Step1: Literature in field of remanufacturing is reviewed and surveyed to conclude the assessment directions, the following assessment approach are found out :-
 - Remanufacturability, technical viability, remanufacturing portfolio or technological path assessment.
 - Economic viability and environmental viability assessment.
 - Economic viability, environmental viability and technical viability assessment.
- 2- Step2: Comparative literature based analysis application.
- 3- Step3: Classification of sample into:
 - Remanufacturability Assessment.
 - Remanufacturing Sustainability Assessment.
 - Partial Remanufacturing Sustainability Assessment.
- 4- Step4: Re-representation of discussions and conclusions.
- 5- Step5: Graphical representation of results.
- 6- Step6: Isolation of criteria.
- 7- Step7: Case study definition.
- 8- Step8: Weighting of criteria.
- 9- Step9: Weighting of satisfaction
- 10- Step10: Global weights calculation.
- 11- Step11: Sustainability Index weights calculation

Figure1 shows comprehensive comparative literature based remanufacturing assessment methodology.

Figure 24: Comparative literature based assessment application methodology



3. Results and discussion

Literature in field of sustainability assessment can be classified into macro-scale literature which assesses sustainability based on general criteria in field of business sustainability assessment and micro-scale literature which assesses sustainability based on specified criteria in field of remanufacturing sustainability assessment. A sample of (35) published paper are used to elicit criteria and their weight to be normalized and unified. Satisfaction local weight of each criterion is calculated to express the sustainability index that may be satisfied by remanufacturing-upgrading of conventional milling machine into CNC machine business. Fuzzy linguistic scale is used to describe four sub-degrees of the satisfaction degree of a criterion based on consideration of remanufacturing business application. Triangular fuzzy numbers are used to differentiate each sub-degree. Criterion weight is described as triangular fuzzy number to describe the importance of a criterion then the local weight of satisfaction can be obtained. Table1 shows macro-scale economic sub-sustainability assessment and table2 shows micro-scale economic sub-sustainability assessment. Both tables include mean local weights of criteria which represent the importance of a certain criterion through the process of sustainability assessment. Satisfaction local weight represents to which extent the process of remanufacturing-upgrading of conventional milling into CNC machine can satisfy a certain criterion. Global economic sub-sustainability assessment weight can be obtained by multiplication of satisfaction local weight by mean local of a criterion .Local weights of criteria help to specify the fuzzification grade of each criterion where local weights are used to put the criteria in an order and prepare them for fuzzication process. Preference of alternatives based fuzzy linguistic matrices construction is applied. The triangular fuzzy numbers are used to construct the matrices of local weights of alternatives evaluation. It is a hybrid approach of comparative literature based analysis and remanufacturing experience based application and triangular fuzzy numbers based matrix mathematical modeling to find out local weights of criteria, local weights of alternatives and global weights of alternatives.

3.1. Economic sub-sustainability assessment index weight

Table 1 and table 2 show the results of economic sub-sustainability assessment of conventional milling machine into CNC machine remanufacturing-upgrading. The results are illustrated in Figure 25 and Figure 26. The global weights of criteria are used to find the index weight which is the mean of these weights to get the values of (0.252) according to macro-scale literature based assessment and (0.215) according to micro-scale literature based assessment.

Figure 25: Global weight vs. satisfaction local weight of economic sub-sustainability assessment, macro-scale literature based assessment

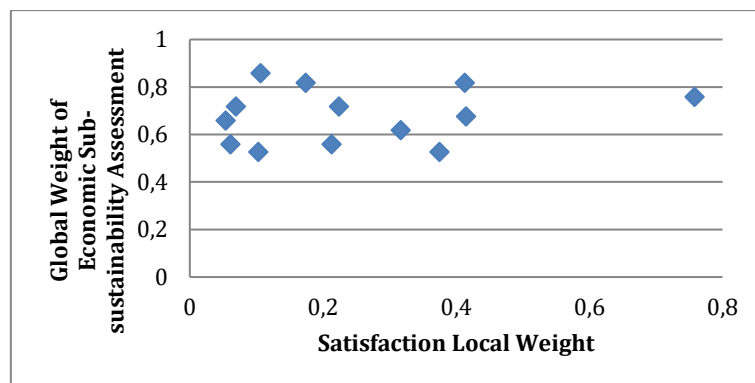


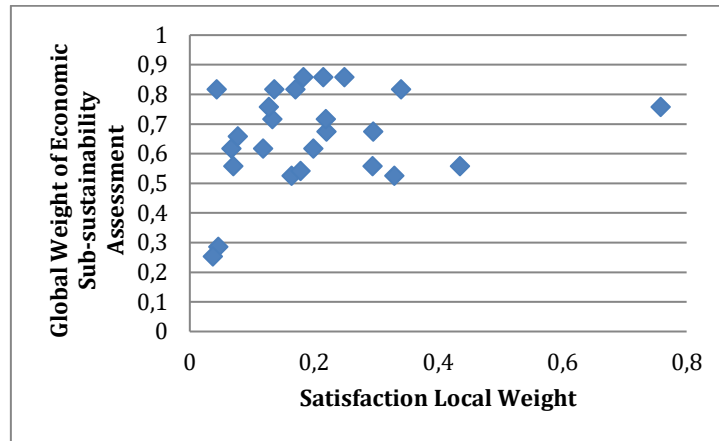
Table 1: Index weight and global weights of economic sub-sustainability assessment, macro-scale literature based assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Sub-sustainability Assessment Weight
Quality	1	0.758	0.758
Delivery	0.713	0.526	0.375
Cost	0.506	0.817	0.413
Technology Capability	0.514	0.617	0.317
Flexibility	0.312	0.717	0.224
Capacity	0.613	0.675	0.415
Lead Time	0.082	0.658	0.054
Financial Capability	0.111	0.558	0.061
Price	0.123	0.858	0.106
Profit	0.096	0.717	0.069
After Sales Services	0.195	0.526	0.103
Raw Material Substitution	0.218	0.817	0.174
Cost Reduction Activities	0.388	0.558	0.213
Mean Global Weight			0.252

Table 2: Index weight and global weights of economic sub-sustainability assessment, micro-scale literature based assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Assessment Weight
Cost	1	0.758	0.758
Time	0.625	0.526	0.329
Service	0.053	0.817	0.043
Quality	0.109	0.617	0.067
Upfront Investment	0.185	0.717	0.133
Profitability	0.326	0.675	0.220
Tax and Subsidy	0.117	0.658	0.077
Cost of Purchasing End-of-life Products	0.780	0.558	0.435
Transportation Cost	0.290	0.858	0.249
Inventory Cost	0.305	0.717	0.219
Remanufacturing Processing Cost	0.312	0.526	0.164
Cost of purchasing replace parts	0.208	0.817	0.170
Economic Re-manufacturability Indicator	0.526	0.558	0.294
Quality Re-manufacturability Indicator	0.125	0.558	0.070
Core Collection	0.416	0.817	0.340
Overheads	0.437	0.675	0.295
Response Time	0.213	0.858	0.183
Execution Time	0.250	0.858	0.215
Reverse Logistics Transport Time	0.192	0.617	0.118
Rental Prices for Integrated Platforms	0.162	0.286	0.046
Cost of Knowledge Services	0.167	0.817	0.136
Cost of Processing and Testing	0.167	0.758	0.127
Default Fine	0.146	0.253	0.037
Service Resources	0.328	0.542	0.178
Service Module	0.323	0.617	0.199
Mean Global Weight			0.215

Figure 26: Global weight vs. satisfaction local weight of economic sub-sustainability assessment, micro-scale literature based assessment



3.2. Environmental sub-sustainability assessment index weight

Table 3 and table 4 show the results of environmental sub-sustainability assessment of conventional milling machine into CNC machine remanufacturing-upgrading. The results are illustrated in figure 27 and figure 28. The global weights of criteria are used to find the index weight which is the mean of these weights to get the values of (0.170) according to macro-scale literature based assessment and (0.294) according to micro-scale literature based assessment.

Figure 27: Global weight vs. satisfaction local weight of environment sub-sustainability assessment, macro-scale literature based assessment

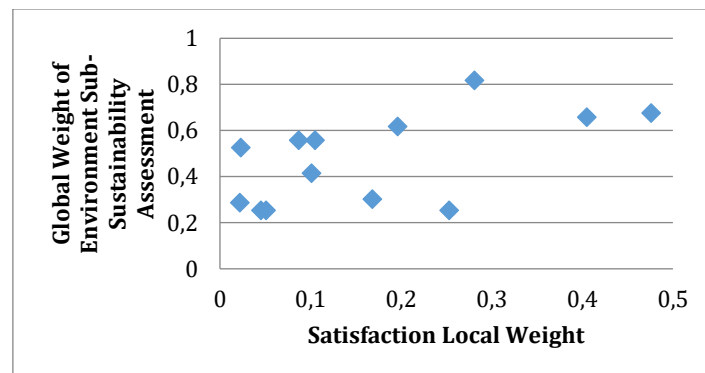


Table 3: Index weight and global weights of environment sub-sustainability assessment, macro-scale literature based assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Sub-sustainability Assessment Weight
Environmental Management System	1	0.253	0.253
Eco-design	0.556	0.302	0.168
Reduce, Reuse and Recycle	0.344	0.817	0.281
Pollution Reduction	0.705	0.675	0.476
Green Production	0.188	0.558	0.105
Energy Consumption	0.317	0.617	0.196
Material Consumption reduction	0.615	0.658	0.405
Eco-labelling	0.202	0.253	0.051

Environmental Commitment	0.244	0.414	0.101
Green Research and Development	0.173	0.253	0.045
Green Process Altering	0.044	0.526	0.023
Environmental Performance Evaluation	0.156	0.558	0.087
Environmental Certification	0.078	0.286	0.022
Mean Global Weight			0.170

Figure 28: Global weight vs. satisfaction local weight of environment sub-sustainability assessment, micro-scale literature based assessment

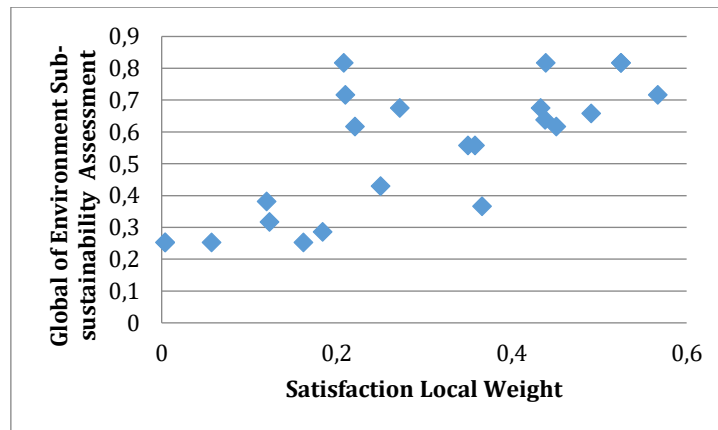


Table 4: Index weight and global weights of environment sub-sustainability assessment, micro-scale literature based assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Assessment Weight
Process Emission Reduction	0.403	0.675	0.272
Process Consumption Reduction	0.687	0.638	0.438
Resource depletion potential Reduction	0.254	0.817	0.208
Global warming potential Reduction	0.582	0.430	0.250
Respiratory inorganics Reduction	0.313	0.382	0.120
Acidification potential Reduction	1	0.366	0.366
Water eutrophication potential Reduction	0.388	0.317	0.123
Material saving	0.746	0.658	0.491
Energy saving	0.731	0.617	0.451
Pollution reduction	0.791	0.717	0.567
Industrial Wastewater emission Reduction	0.642	0.817	0.525
Industrial exhaust fumes Reduction	0.627	0.558	0.350
Industrial solid waste Reduction	0.642	0.558	0.358
The utilization rate of environmentally friendly materials	0.642	0.253	0.162

Rate of remanufacturing for end-of-life products	0.642	0.675	0.433
Rate of material reuse	0.537	0.817	0.439
Rate of material recovery	0.642	0.817	0.525
Other Material recourse consumption	0.642	0.286	0.184
Resource consumption indicator	0.015	0.253	0.004
Environmental emission indicator	0.015	0.253	0.004
Analysis of abiotic depletion	0.224	0.253	0.057
Primary energy depletion reduction	0.418	0.717	0.210
Particulate Matter reduction	0.358	0.617	0.221
Mean Global Weight			0.294

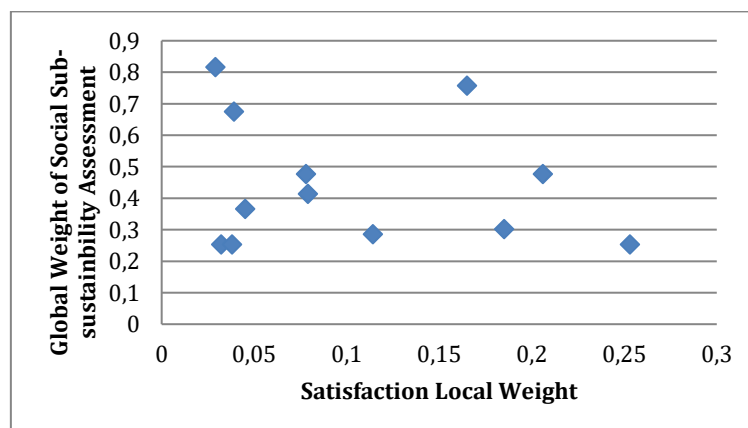
3.3. Social sub-sustainability assessment index weight

Table 5 shows the results of social sub-sustainability assessment of conventional milling machine into CNC machine remanufacturing-upgrading. The results are illustrated in figure 29. The global weights of criteria are used to find the index weight which is the mean of these weights to get the values of (0.105) according to both of macro-scale literature based and micro-scale literature based assessments.

Table 5: Index weight and global weights of social sub-sustainability assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Sub-sustainability Assessment Weight
Occupational Health and Safety	1	0.253	0.253
Employee Right	0.611	0.302	0.185
Training and Education	0.432	0.477	0.206
The Rights of Stakeholders	0.218	0.758	0.165
Information Disclosure	0.127	0.253	0.032
Social Commitment	0.123	0.366	0.045
Supportive Activities	0.399	0.286	0.114
Ethical Issues and Legal Compliance	0.149	0.253	0.038
Employment Relationships	0.192	0.414	0.079
Innovation Level	0.164	0.477	0.078
Ergonomics	0.058	0.675	0.039
Green perception	0.035	0.817	0.029
Mean Global Weight			0.105

Figure 29: Global weight vs. satisfaction local weight of social sub-sustainability assessment



3.4. Management sub-sustainability assessment index weight

Table 6 shows the results of management sub-sustainability assessment of conventional milling machine into CNC machine remanufacturing-upgrading. The results are illustrated in figure 30. The global weights of criteria are used to find the index weight which is the mean of these weights to get the values of (0.154) according to both of macro-scale literature based and micro-scale literature based assessments.

Figure 30: Global weight vs. satisfaction local weight of management sub-sustainability assessment

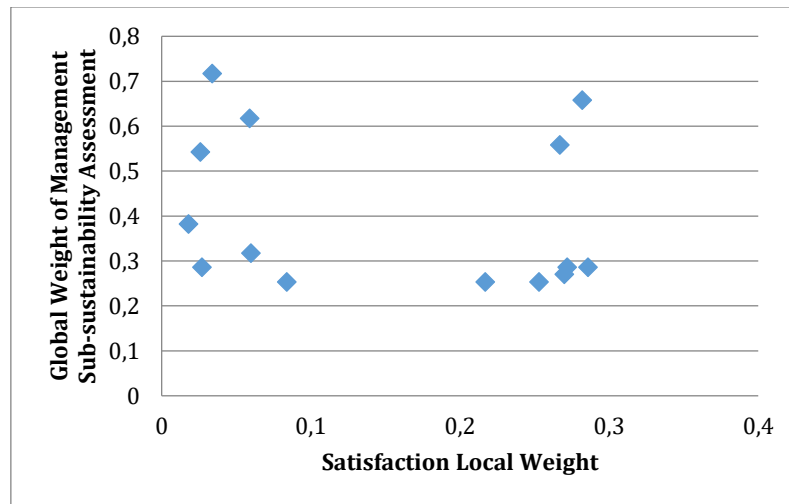
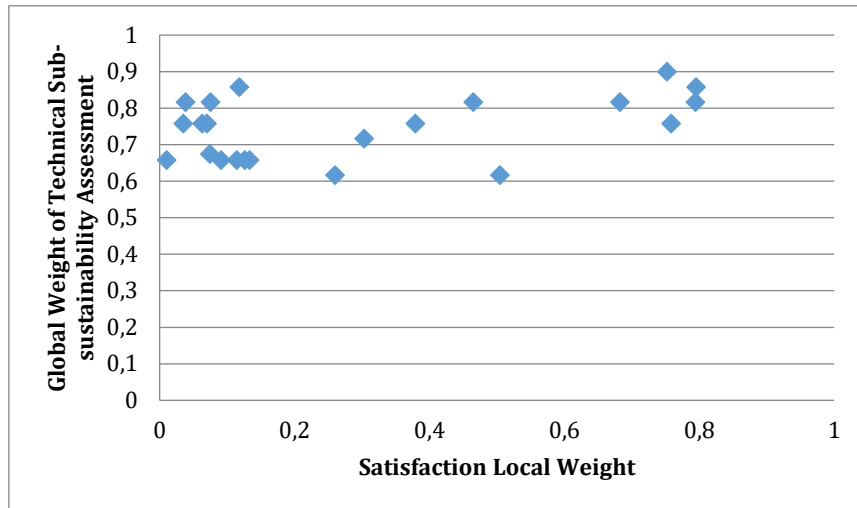


Table 6: Index weight and global weights of management sub-sustainability assessment

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Assessment Weight
Protection of Intellectual Property	0.333	0.253	0.084
Government Regulations	0.952	0.286	0.272
Integrated Organizational Alignment	0.857	0.253	0.217
Brand Erosion	0.095	0.286	0.027
Talent Quality	0.190	0.317	0.060
Standard Performance	0.429	0.658	0.282
Quality Certification	0.095	0.617	0.059
Information Management	0.048	0.717	0.034
Recovery Network	0.048	0.382	0.018
Sale Model	0.048	0.542	0.026
Market Strategy	0.476	0.558	0.267
Network Operation	1	0.253	0.253
Knowledge Transfer	1	0.270	0.270
Information Storage	1	0.286	0.286
Mean Global Weight			0.154

3.5. Technical sub-sustainability assessment index weight

Table 7 shows the results of technical sub-sustainability assessment of conventional milling machine into CNC machine remanufacturing-upgrading. The results are illustrated in figure 31. The global weights of criteria are used to find the index weight which is the mean of these weights to get the values of (0.288) according to both of macro-scale literature based and micro-scale literature based assessments

Figure 31: Global weight vs. satisfaction local weight of technical sub-sustainability assessment**Table 7: Index weight and global weights of technical sub-sustainability assessment, micro-scale**

Criterion	Mean Local Weight	Satisfaction Local Weight	Global Economic Assessment Weight
Accuracy	0.500	0.758	0.379
Reliability	0.835	0.817	0.682
Processing Efficiency	0.422	0.717	0.303
Processing Range	0.422	0.617	0.260
Bonding strength	0.192	0.658	0.126
Hardness	0.110	0.675	0.074
Porosity Reduction	0.083	0.758	0.063
Substrate deformation	0.015	0.658	0.010
Recoverability	0.138	0.858	0.118
Design Issues Satisfaction	0.092	0.758	0.070
Materials Matching	0.092	0.817	0.075
Disassembly	0.927	0.858	0.795
Cleaning	0.817	0.617	0.504
Inspection and sorting	1	0.758	0.758
Reconditioning	0.972	0.817	0.794
Upgrading	0.835	0.9	0.752
Reassembly	0.569	0.817	0.465
Damage Type Definition	0.174	0.658	0.114
Damage Location Definition	0.202	0.658	0.133
Damage Degree Definition	0.138	0.658	0.091
Equipment Utilization	0.046	0.758	0.035
Original Equipment Specifications	0.046	0.817	0.038
Restoration	0.046	0.817	0.038
Design for Remanufacturing	0.303	0.675	0.205
Testing Technology	0.083	0.717	0.060
Technology	0.303	0.817	0.248
Scale	0.431	0.758	0.327
Mean Global Weight			0.288

4. Conclusion

Summation of comprehensive sustainability assessment index weights that are calculated based on micro-scale literature exceed consistency value to be (1.056) while summation of comprehensive assessment index weights that are calculated based on macro-scale literature is within the limit of consistency value to be (0.969). Mean of both summations is of value of (1) so results of comprehensive sustainability assessment are consistent, figure32 and table 8 includes index weights variation.

Index weights of economic and technical sub-sustainabilities are the highest according to macro-scale literature based comprehensive sustainability assessment, while environmental and technical sub-sustainabilities are the highest index weights according to micro-scale literature based comprehensive sustainability assessment. Environmental sub-sustainability is of the highest weight when micro-scale is compared with macro-scale. Social sub-sustainability is of the lowest index value to be followed by management sub-sustainability which means these areas are interlinked and need to be studied further for developing. According to values of index weights, economic, environment and technical perform well toward comprehensive sustainability.

Literature is surveyed in directives of:

- Sustainability assessment
- Remanufacturability assessment
- Technique for order performance by similarity to ideal solution based assessment.

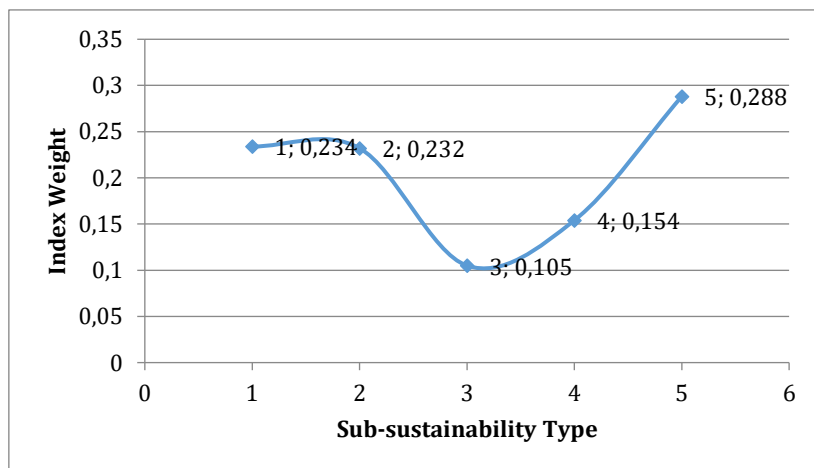
Local weights of criteria are elicited to be matched with triangular fuzzy numbers to enable proposing of intermediate local weights based regression. Integrated framework of global weights is constructed to simulate sub-sustainability based analysis. Fuzzy linguistic expression are used to differentiate between four degrees of fuzzication intensity for each satisfaction degree of a criterion to apply regression among them to find the local weight to be multiple by the criteria weight to find out the global weight of sub-sustainability assessment. Mean global weight of sub-sustainability assessment is calculated to be the index weight that indicates the satisfaction of certain sustainability.

Mixture of literature comparisons and practical application of remanufacturing-upgrading of conventional milling into CNC machine are exploited to describe different sub-sustainabilities assessments of remanufacturing-upgrading process. Comprehensive sustainability assessment is a group of sub-sustainabilities to be conducted to find out the degree of applicability of development.

Table 8: Sub-sustainability index weights

Sub-sustainability	Index Weight
Economic sub-sustainability	0.234
Environmental sub-sustainability	0.232
Social sub-sustainability	0.105
Management sub-sustainability	0.154
Technical sub-sustainability	0.288

Figure 32: Sub-sustainability assessment index weight variation



Not only human indications about experience are required to be expressed for fuzzy elimination but also highly variety sustainability literature itself is required to be unifying through fuzzification. As example, sustainability indicators are measures of economic, environment, social, management and technical performances which are numbered criteria that suffered from bifurcation.

Economic criteria are of high number and weight, environment criteria are of high number and high weights, social criteria of low number and weights, management criteria of low number and weights, and technical criteria of low number and high weights. Weights of criteria put them in the order of technical, economic, environment, management and social starting with criteria of stronger effect and highest importance.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.14254/jems.2020.5-2.3>

Citation information

Abdullah, Z. T. (2020). Conventional milling into CNC machine tool remanufacturing: Sustainability modeling. *Economics, Management and Sustainability*, 5(2), 39-65. doi:10.14254/jems.2020.5-2.3

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