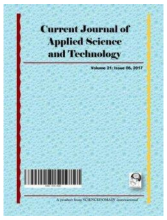


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# Conventional Milling Machine into CNC Machine Tool Remanufacturing, Eco-comparison Ratio Based Analysis

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Author ZTA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors GSS and SBY managed the analyses of the study. Author ZTA managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

**Aims:** Machine tool remanufacturing input material, energy and $Co_2$ emissions are assessed to help conclude feedbacks about environmental benefits and burdens, what is necessary to enable educational institutions to conduct remanufacturing of machine tools as a business to deliver closing the loop supply chain for sustainable manufacturing.
**Study Design:** Bridgeport manual milling machine is remanufactured within insights of new eco-design ideas to change it into CNC vertical milling machine where machine enabled to be flexible to embed cheap emerged CNC technology. Thus enough data can be acquired to be analyzed for feasibility study.
**Methodology:** A step by step case study of CNC machines technology introduction into conventional machine architecture is illustrated. Modules of ball screws and ball linear guide ways

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are embedded by means of magnetic mechanical flexible interfaces. Servo motors and CNC controller are used to deliver computer numerical control. Literature comparison and calculation are made to find eco-audit of the remanufacturing process.

**Results:** Melting point of N35 Neodymium is compared with mean melting point of Cast Iron to exploit well-defined eco-audit of Cast Iron literature through defining ECR (eco-comparison ratio).

**Conclusion:** To fulfill remanufacturing, eco-design enables modules of linear slides rails-carriages and ball lead screws to be assembled to conventional milling machine, which can be certain through magnetic pots based mechanical interface. Comparative eco-audit of technological path for CNC technology integration is required to optimize eco-innovation strategy to deliver sustainable remanufacturing. Such integrated platform of machine tool remanufacturing based on both emerged lower cost CNC technology adoption and capabilities of institutes of technology where the hybrid labor-student remanufacturing environment can be certain to deliver hybrid public-private services that is aimed to establish triple bottoms of economic, environmental and social sustainability.

*Keywords: Comparative eco-audit; conventional milling machine into remanufacturing; CNC machine tool remanufacturing; assembly based remanufacturing and magnetic pots eco-audit comparison.*

## NOMENCLATURES

| | |
|---|---|
| $ECR$ | : Eco-comparison ratio |
| $W_{CMT}$ | : Total weight of conventional milling machine (kg) |
| $IP_{PNM}$ | : Input energy of primary manufacturing of neodymium magnets (MJ/kg) |
| $IP_{PC}$ | : Input energy of primary manufacturing of cast iron (MJ/kg) |
| $IP_{Ps}$ | : Input energy of primary manufacturing of steel (MJ/kg) |
| $IP_{SNM}$ | : Input energy of secondary manufacturing of neodymium magnets (MJ/kg) |
| $IP_{SC}$ | : Input energy of secondary manufacturing of cast iron (MJ/kg) |
| $IP_{SS}$ | : Input energy of secondary manufacturing of steel (MJ/kg) |
| $IP_{CMT}$ | : Input energy of primary manufacturing of conventional machine tool (MJ) |
| $IS_{CMT}$ | : Input energy of secondary manufacturing of conventional machine tool (MJ) |
| $O_{PCO2C}$ | : Output $Co_2$ emission of primary manufacturing of cast iron (kg/kg) |
| $O_{PCO2s}$ | : Output $Co_2$ emission of primary manufacturing of steel (kg/kg) |
| $O_{PCO2NM}$ | : Output $Co_2$ emission of primary manufacturing of neodymium magnets (kg/kg) |
| $O_{SCO2C}$ | : Output $Co_2$ emission of secondary manufacturing of cast iron (kg/kg) |
| $O_{SCO2s}$ | : Output $Co_2$ emission of secondary manufacturing of steel (kg/kg) |
| $O_{SCO2NM}$ | : Output $Co_2$ emission of secondary manufacturing of neodymium magnets (kg/kg) |
| $O_{PCO2CMT}$ | : Output $Co_2$ emission of primary manufacturing of conventional machine tool (kg) |
| $O_{SCO2CMT}$ | : Output $Co_2$ emission of secondary manufacturing of conventional machine tool (kg) |
| $P_E$ | : Embodied energy of conventional milling machine remanufacturing into CNC milling machine (MJ) |
| $IP_{PRM}$ | : Input energy of primary manufacturing of remanufacturing materials (MJ) |
| $IP_{SPRM}$ | : Input energy of secondary manufacturing of remanufacturing materials (MJ) |
| $IP_{TPCMT}$ | : Total input energy of primary manufacturing of conventional milling machine (MJ) |
| $IP_{TSCMT}$ | : Total input energy of primary manufacturing of conventional milling machine (MJ) |
| $IP_{TR}$ | : Total input energy of remanufacturing operations (MJ) |
| $O_{TCO2}$ | : Total output $Co_2$ emissions (kg) |
| $O_{TCO2PRM}$ | : Total output $Co_2$ emissions of primary manufacturing of remanufacturing materials (kg) |
| $O_{TCO2PRM}$ | : Total output $Co_2$ emissions of primary manufacturing of remanufacturing materials (kg) |
| $O_{TCO2PCMT}$ | : Total output $Co_2$ emissions of primary manufacturing of conventional machine tool (kg) |
| $O_{TCO2SCMT}$ | : Total output $Co_2$ emissions of secondary manufacturing of conventional machine tool (kg) |
| $O_{TCO2R}$ | : Total output Co2 emissions of remanufacturing operations (kg) |

## 1. INTRODUCTION

Achieving ecosystem-based sustainability necessitates thinking to understand the implications of new policies and practices, and define the linkages and flows of sustainable value creation to come out of collaborative economic, societal, and environmental systems to eliminate harm consequences of manufacturing. Integrated assessment of the costs and benefits of sustainable materials management through such dynamic model enables dematerialization to be pursued using a variety of regulatory and voluntary approaches based remanufacturing business as sociotechnical transitions integration. This allow to define inertia of environmental impact reduction which is a dynamic system of sustainability through closed supply chain with reverse logistics and remanufacturing of used products with considerable shift from products to services. Such remanufacturing based sustainability is delayed by the most diffused landfill and materials recycling end-of-life practices. So technology, methodology and business oriented innovations are needed to develop enablers of educational institutions internet of things, educational institutions based data acquisition application, cloud storage and cloud manufacturing platform, eco-design and product service system for remanufacturing as a service of cloud manufacturing. Thus, energy footprint and the raw material consumption are directly affected through closing of both supply chain and product lifecycle by remanufacturing as a service [1,2]. Such closed loop supply chain based sustainability delivers sustainable manufacturing strategies with resource and environment conservation. Scientific literature should be shifted on the closed loop systems presents to realize resource conservative manufacturing. Such conservation of energy, material and value added with waste prevention and environment protection are integrated components of eco-design and remanufacturing. This can lead development strategy of multiple lifecycles innovative where closed loop supply chain design, business models and customers are integral parts of collaborative manufacturing [3]. Remanufacturing is a promising strategy, but there is a necessary need to explore it for formal activities and certain whether remanufactured products are accepted to be fitted into market. Remanufacturing activities are still in nascent stages and recent growth economy coupled with serious issues of population and environmental burden which demands a radical shift in market strategies and legislations to cope scattered and inefficient product recovery and increased environmental and economic burdens on the society [4]. Sustainable optimal design and planning of supply chains cultivate growing awareness which balancing social, environmental and economic objectives to guarantee long term sustainability. Inventory management, product design, production planning and control for remanufacturing, product recovery, reverse logistics and closed-loop supply are sustainable production to energy efficiency and waste and resources sustainable management [5]. Sustainability and environmental protection are key factors of reduced resource consumptions, environmental friendly manufacturing and an optimized long customer usage phase. High development, production costs, high innovation rates and customer usage extension associated resources saving through services lightened product physicality. Relationship, complexity and the interdependences of layout planning and product design, manufacturing planning and the use phase combine the characteristics of sustainability and reliability toward comprehensive eco-design of new product and closed product lifecycle [6]. It can be concluded to state that, remanufacturing is the ultimate form of recycling can restore the used products of high value-added, with great advantages of energy saving and emission-reduction. The environmental benefits of machine tool remanufacturing can be evaluated in terms of energy saving, material saving and pollution reduction. Machine tool is of great recycling value and potential for remanufacturing and of absolute remanufacturability [7]. Closed-loop production systems and closed-loop supply chains can be achieved using different approaches and strategies to contribute both of the reduction of negative environmental impact and increasing of economic benefits. This will improve sustainability and lead to improvements in environmental performance of an organization. Closed loop, life cycle issues, end of life and total life cycle are current literature directives to help developing of sustainable manufacturing as shown in Fig. 1 [8]. Closed loop product life cycle and closed loop supply chain require the application of remanufacturing activity to close the supply chain and predominate sustainable manufacturing what is highlighted through the work of Moldavska and Welo, Abullah et al. [8,9]. Sustainable development, such as closed loop sustainable manufacturing, is recognized as a long-term oriented strategy to concern both current and future generations by combining short-term and long-term goals. But even long-term perspective is essential for manufacturing organizations to achieve sustainable development, analysis can show that the time perspective is taken rarely with emphasize on short-term thinking for sustainability but the need to focus on both long and short-term aspects is highly required [8]. Growing concern about the environment burdens coming from waste, carbon emissions and landfill has spurred research into the field of remanufacturing of industrial equipment especially for machine tool due to high degree of remanufacturability of machine tools. This study aims to introduce the projection of eco-audits literature to conduct calculation of remanufacturing based on eco-comparison. Magnetic pots are made of N35 Neodymium and since literature with few eco-audits about such material, comparison is conducted with Cast Iron due to similarity of physical properties. Assembly for linear ball guides, Fig. 1, to increase design for remanufacturing through increasing assembly-disassembly, without any need to drill the old guides for application of substitution technology, Table 1, for screw assembly of worn machine tool guides with new linear guides of ball carriages to reduce friction and lubrication. New linear guides and ball carriages are assembled on the old worn slides by using magnetic pots to substitute the worn machine tools slides, vertical turret conventional milling machine to be remanufacturing into CNC machine tool. Additive operations and machining operations are eliminated, Fig. 2, remanufacturing time is reduced and environmental criteria are highlighted. Machine tool wear of both screw and slides cannot be treated by additive technology of arc welding, thermal spraying or thermite welding. Such technologies should numerically controlled by computer to eliminate any need for further finishing and surface treatment processes. The key factors are to reduce backlash and friction and lubrication using which cannot be realized without CNC machine technology embedding within old machine tools which can be possible by magnetic pots assembly to establish the bases for meaningful of embedding other CNC technologies. Machine tool remanufacturing has appeared in machinery companies in developed countries because machine tool is of great remanufacturability value and potential for remanufacturing [10], through high disassembly. The study states a problem to provide training environment that simulates CNC machine tools operation to produce complex shapes with minim accuracy that suitable for daily life products that made of plastic. The study maps the machine tool remanufacturing according to educational institutions infrastructures as a triple sustainability approach that includes:-

1- Social criteria: provide a training environment that simulates CNC machine tools to increase the trustful of student about what they study, human development and employment based on both of remanufacturing and CNC machine tools technologies. Thus pro-environment, environment education and sustainable consumption can be long life education and learning technology that starts at institutes of technology to help emerging of remanufacturing societies of sustainable consumption.
2- Economic criteria: Using CNC technology that made by emerging countries to reduce the cost [14] according to using of :-
   - Ball screw accuracy is 0.3 mm.
   - Open loop CNC controller is cheap technology comparing with closed loop control system.
   - Reduce remanufacturing time. Ball screw, brackets, ball bearings and holders assembly are required standard human energy, Table 2, and time. Practical application and comparative literature measures are used to find out the human energy ranges. Linear guides of magnetic assembly are required very lower time than drilling and tapping for screw assembly.
3- Environment criteria: energy and related $Co_2$ emissions will be reduced through remanufacturing activities and during machine tool working due to reduction of friction and lubrication using can highlight environment protection as a consequent of CNC machine tools adoption [13].

Since study aims to reduce activities of remanufacturing to be disassembly , cleaning and assembly only so that an educational institution can perform remanufacturing of educational instrument and training machine by exploiting human power of students based practical sallybuses such as workshops and graduation projects. To assess maximum and minimum values of human power required for machine tool assembly based remanufacturing three methods can be used as eco-comparison based assessment , comparative literature assessment as following:

1- Expert consultation
2- Comparative literature study
3- Practical application of assembly based remanufacturing

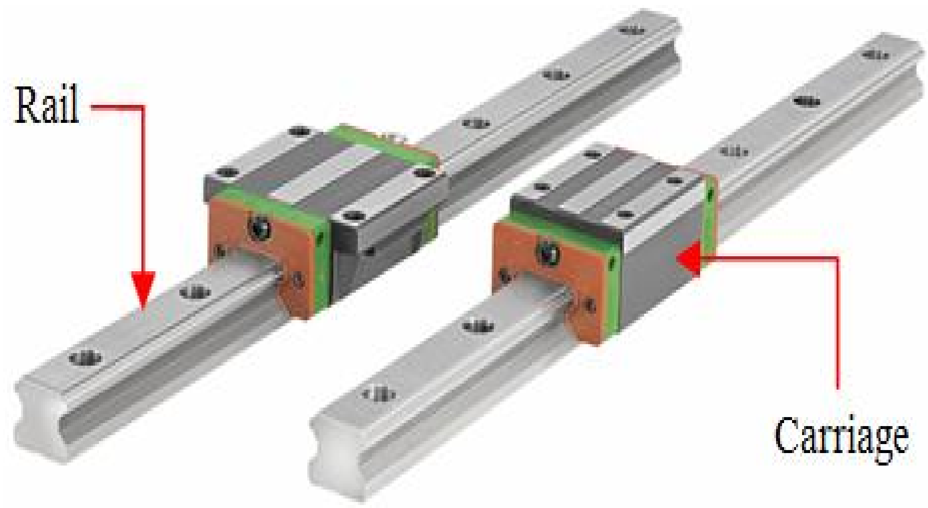


**Fig. 1. Linear ball sides of rail and carriage**

**Table 1. Alternatives of remanufacturing technology [10]**

| End-of-life status | Required remanufacturing operations | Technology alternatives |
|---|---|---|
| Wear, nicks and dents, or corrosion | Magnetic assembly | Human power assembly and disassembly |
| Wear, nicks and dents, or corrosion | Additive Operations | Arc welding thermal spraying or thermite welding |
| Wear, nicks and dents, or corrosion | Machining operations | Drilling and tapping or grinding and polishing |

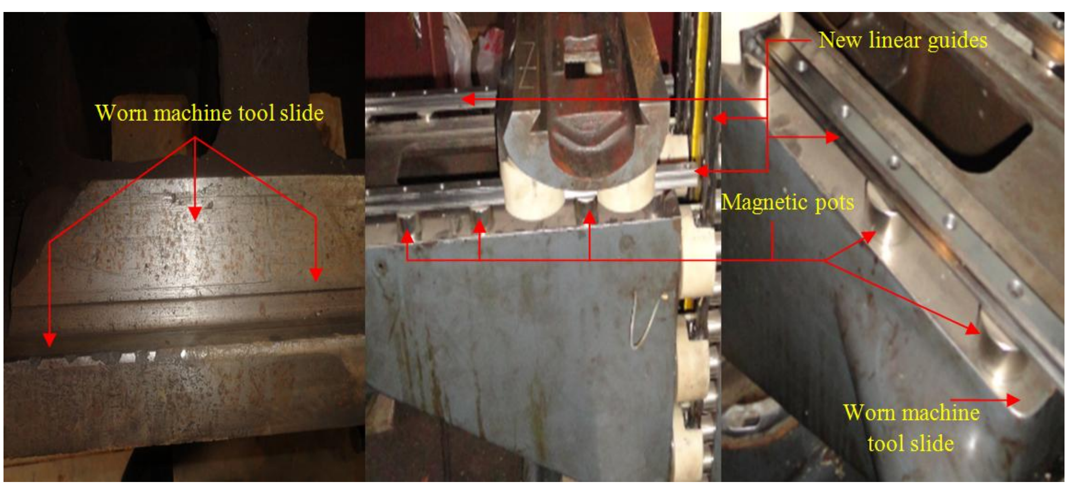


**Fig. 2. Substitution of worn machine tool slides by new linear guides of ball carriages by application of magnetic pots assembly**

**Table 2. Comparative distribution of human power according to assembly of machine tool activity, based on comparison with [11,12]**

| Assembly activity | Power (watt) Max. | Power (watt) Min. |
|---|---|---|
| Disassembly and cleaning of machine column, knee, saddle and ram. | 286 | 116 |
| Magnetic pots to Y-Z axes saddle assembly. | 128 | 116 |
| Ball carriage of linear slide assembly. | 128 | 116 |
| Magnetic pots guards' assembly | 128 | 116 |
| Y-Z axes saddle cleaning and preparation. | 175 | 116 |
| Rail of linear slides for Y-Z axes saddle assembly. | 163 | 128 |
| Magnet pots for Y-Z axes saddle to machine column assembly | 268 | 116 |
| Z-axis saddle and machine column assembly | 268 | 116 |
| X-Y axes saddle to main frame assembly | 268 | 163 |
| X-Y axes Yoke and connection nuts and screw assembly | 268 | 163 |
| Fly cutting to half Yoke into upper and lower parts of X-Y axes and X-Y axes ball | 268 | 163 |
| Ball screw and lower Yoke assembly | 268 | 163 |
| Linkage of X-Y assembly preparation | 128 | 116 |
| Turning of Yoke halves to inset connection screw and nut | 286 | 163 |
| Nut of X-Y linkage assembly | 286 | 163 |
| Brackets and ball bearing for ball screw assembly | 286 | 128 |
| Linear slide carriages assembly | 128 | 116 |
| Magnet pots and their guards' assembly | 128 | 116 |
| Ball screw of Y-axis to saddle and Yoke assembly | 268 | 163 |
| X-Y saddle preparation for ball screw of X-axis assembly | 128 | 116 |
| Linear slides rails assembly | 128 | 116 |
| X-Y linkage assembly | 286 | 163 |
| Column, ram and Z-axis holding plate assembly | 286 | 128 |
| Preparation of column for Z-axis and ram assembly | 128 | 116 |
| Linear slides rails and table assembly | 268 | 128 |
| Z-axis lower ball bearing assembly | 268 | 128 |
| Z-axis lower ball bearing, left and right positions assembly | 268 | 163 |
| Upper and lower plates of Z-axis holding assembly | 268 | 163 |
| Servo motors assembly | 268 | 163 |
| CNC controller assembly | 268 | 163 |

## 2. ECO-DESIGN AND REMANUFACTURING APPLICATION PROCEDURE OF VERTICAL TURRET CONVENTIONAL MILLING MACHINE INTO CNC MILLING MACHINE

Eco-Design changes to fulfill Remanufacturing include the following procedures:

(1). Magnetic force exploiting to assembly two rails of linear slides to the Column in the direction of Z-axis to substitute the male slide of the column,Fig.3.

(2). Magnetic force exploiting to assembly six carriages of linear slides to the knee in the direction of Z-axis to substitute the female slide of the knee, Fig. 3.

(3). Magnetic force exploiting to assembly two rails of linear slides to the Knee in the direction of Y-axis to substitute the male slide of the Knee.

(4). (4) Magnetic force exploiting to assembly four carriages of linear slides to the bottom of the saddle in the direction of Y-axis to substitute the male slide of the saddle. (6) Magnetic force exploiting to assembly four carriages of linear slides to the top of the saddle in the direction of X-axis to substitute the female slide of the saddle.

(5). Magnetic force exploiting to assembly two rails of linear slides to the bottom of the Table to substitute the male slide of the table.

(6). Substitution of X-axis screw by ball screw with its bearings and nut.

(7). Substitution of Y-axis screw by ball screw with its bearings and nut.
(8). Substitution of Z-axis screw by two ball screws with their bearings and nuts.
(9). Bolt assembly of an Aluminum plate to the bottom of the knee to facility of two ball screws assembly to Z-axis.
(10). Assembly of Cast Iron plate between the column and the ram of the machine to facility of two ball screws assembly to Z-axis.
(11). Assembly of three Aluminum plates at each side of the machine through Cast Iron plate to facility of two ball screws assembly to Z-axis.
(12). Assembly of two steel guide shafts at each side of the machine through three Aluminum plates to facility of two ball screws assembly to Z-axis.
(13). Assembly of two steel guide shafts at each side of the machine through three Aluminum plates to facility of two ball screws assembly to Z-axis.
(14). Assembly of two steel guide shafts at each side of the machine through middle Aluminum plate and the alumina plate that assembled to the bottom of the knee to facility of two ball screws assembly to Z-axis.
(15). Standard bearings and customized flanges are used to satisfy ball screw assembly.
(16). Assembly of servo motors through coupling using.
(17). Assembly of 1:1 pulleys ratio to enable AC motor inventor connection to control the rotation speed of the spindle.
(18). Servo driver and CNC machine control to deliver computer numerical control of the machine as the top of the procedures of remanufacturing conventional milling machine into CNC milling machine.
(19). Yoke is divided into two pieces to be assembled by nut and screw between them to acquire flexibility that is needed to substitute the increasing of distances between knee-saddle and saddle-table due to rails, carriage and magnetic pots assembly.

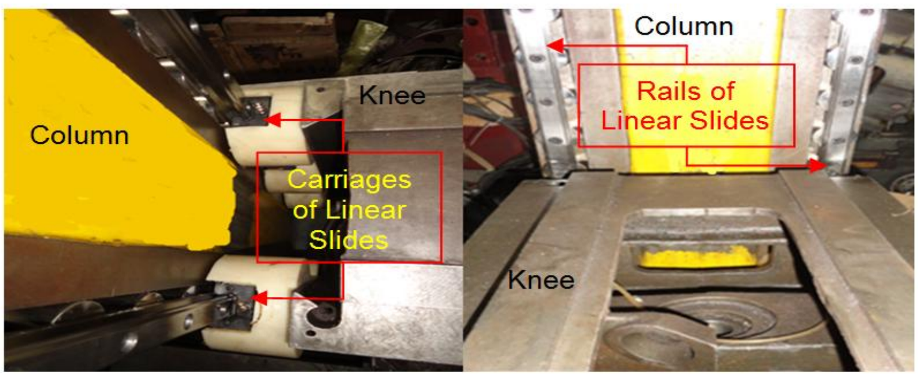


**Fig. 3. Knee to column assembly, flexible fasteners approach**

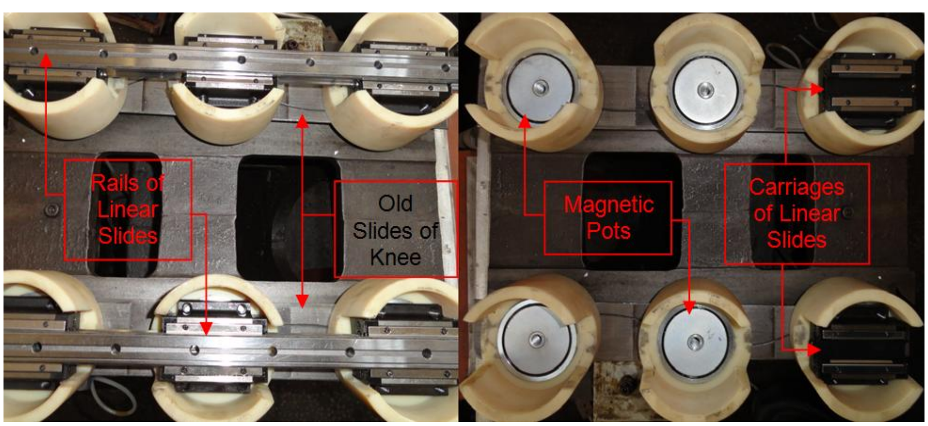


**Fig. 4. Ball linear slides (Rail + Carriage) to column-knee assembly**

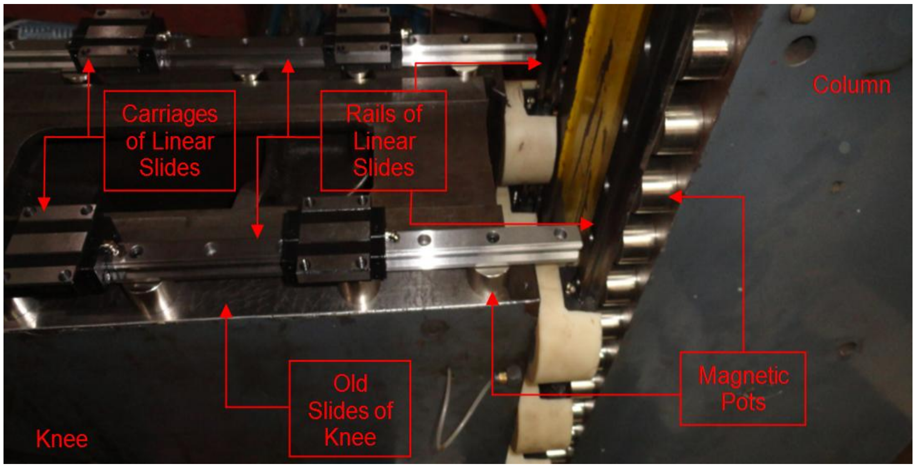


**Fig. 5. Ball linear slides (Rail + Carriage) to knee-saddle assembly**

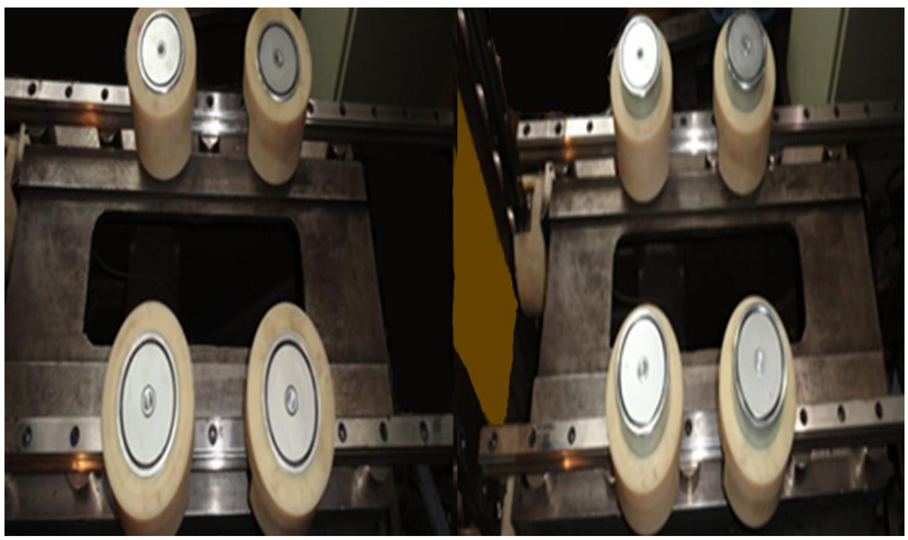

**Fig. 6. Carriages, guards and magnetic pots to fulfill knee-saddle assembly**


**Fig. 7. Column, knee and saddle assembly**

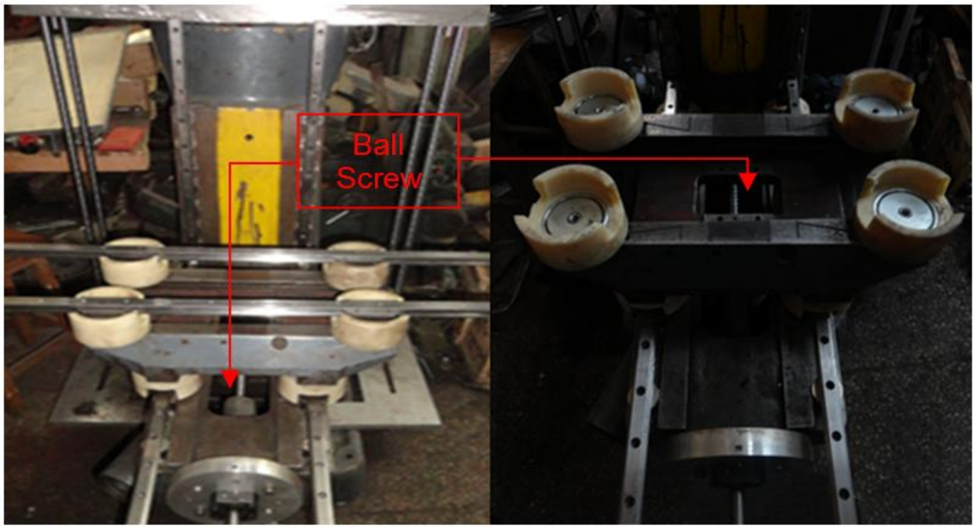


**Fig. 8. Magnetic pots, carriages and rails to fulfill saddle–table assembly**

## 3. CONVENTIONAL VERTICAL TURRET MILLING MACHINE REMANUFACTURING INTO CNC MACHINE TOOL ECO-AUDIT

Magnetic pots are of two parts: the steel housing , figures 9 and 10, and N35 Neodymium disc, Figs. 11 and 12. Table 3 is theoretical energy and $Co_2$ emissions of primary manufacturing of raw Neodymium. Theoretical data of machining of steel housings and parts to facility remanufacturing are listed in Tables 4 and 5. Tables 6 and 7 are input energy and output $Co_2$ emissions of primary and secondary manufacturing of materials and parts to fulfill eco-design and remanufacturing application. Melting point of Neodymium magnets is compared to medium melting point of Cast Iron to find input energy and output $Co_2$ emissions, input energy (MJ/kg) and output $Co_2$ emission (kg/kg) of Cast Iron are of standard values according to Ashby [13]. Magnetic pots are of two parts, one is the N35 Neodymium discs and the second is steel housing. For 90 mm magnetic pots that consist of N35 Neodymium disc of 70 mm diameter, Fig. 11, which is inserted in steel housing of 90mm diameter, Fig. 9. And for 40 mm magnetic pots that consist of N35 Neodymium disc of 35mm diameter, Fig. 12, which is inserted in steel housing of 40mm diameter, Fig. 10 so they work as one unit.

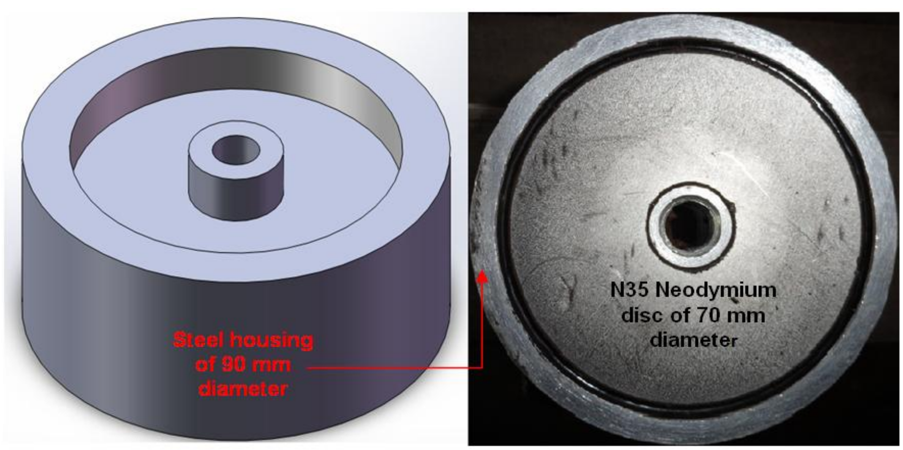


**Fig. 9. Steel housing of 90 mm diameter of magnetic pot of 70 mm diameter used for table, knee and saddle to machine column assembly**

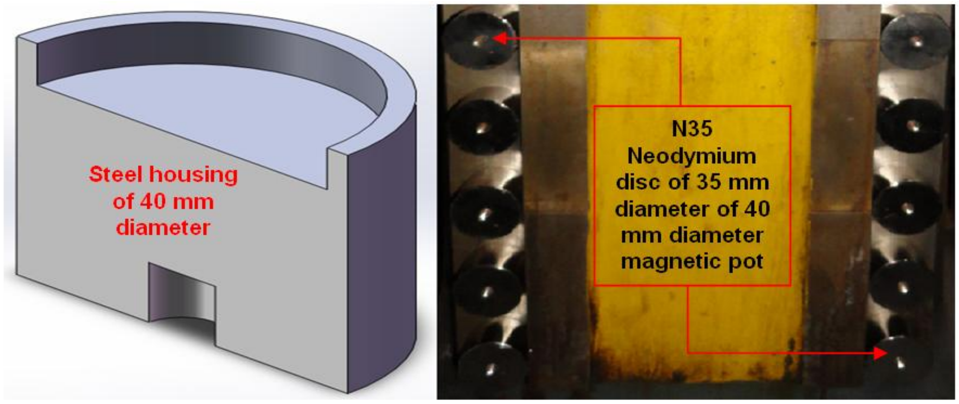


**Fig. 10. Steel housing of 40 mm diameter of magnetic pot of 35 mm diameter used for linear slide to machine assembly**

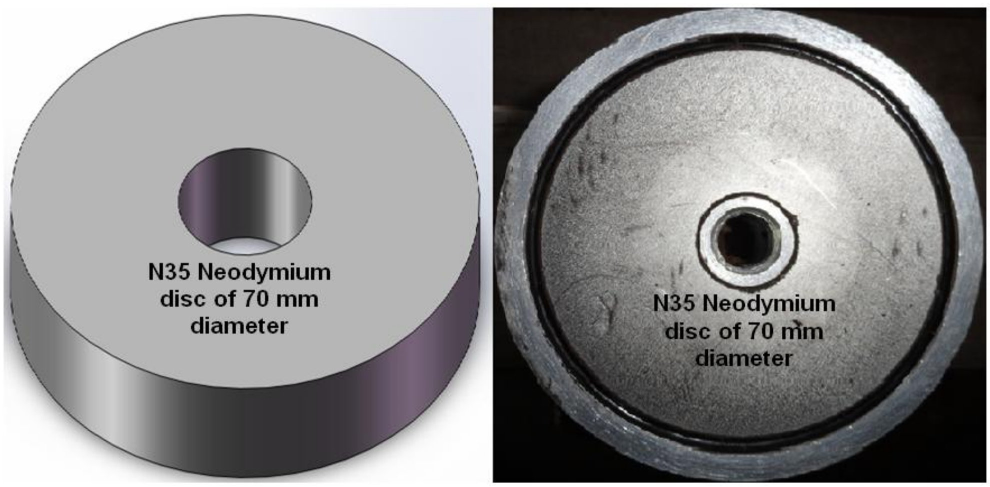


**Fig. 11. N35 Neodymium ring of 70 mm diameter of 90 mm diameter magnetic pot used for table, knee and saddle to machine column assembly**

**Table 3. Power of primary manufacturing of raw Neodymium**

| Operation name | Number of operations | Power (kW) | Power (kWh) | Power (MJ) | $Co_2$ emissions (kg) |
|---|---|---|---|---|---|
| Powder Milling | - | - | - | - | - |
| Pressing | 20 | 4.24 | 84.78 | 834.95 | 55.95 |
| Sintering | 10 | 4.24 | 42.40 | 394.32 | 27.98 |
| Strip casting | - | - | - | - | - |

**Energy (MJ) and $Co_2$ emissions (kg) are calculated based on conversion tables of Ref. [13]*

ECR = Melting point of Neodymium / Medium melting point of Cast Iron (1)

ECR = 1016/1190 = 0.854

Based on ECR (eco-comparison ratio), it can be exploited to find out primary manufacturing of N35 Neodymium magnetic pots:

$IP_{PC}$ = 20 MJ/kg [11]

ECR = 0.854

$IP_{PNM} = IP_{PC} \times ECR = 20 \times 0.854 = 17.08$ MJ/Kg (2)

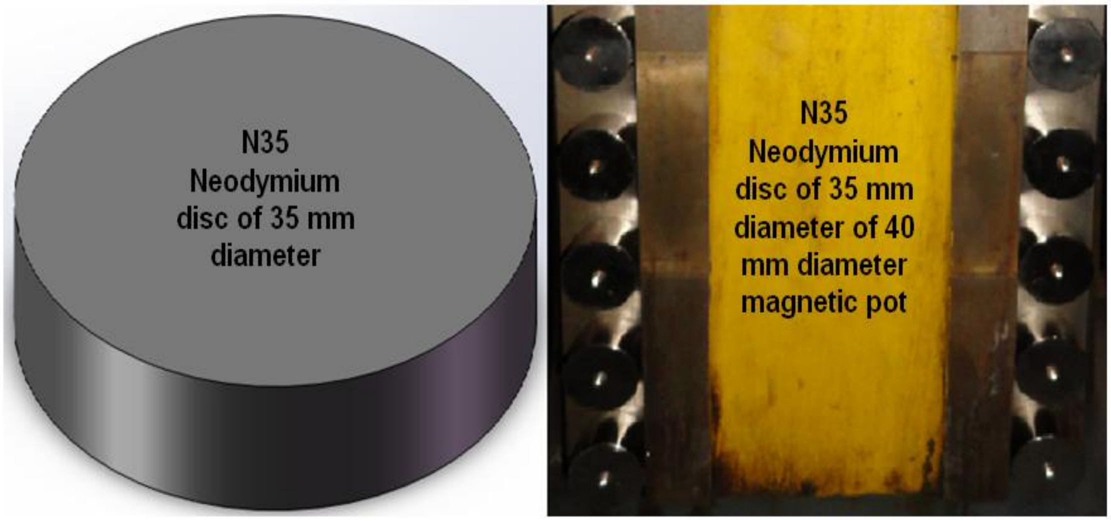


**Fig. 12. N35 Neodymium disc of 35 mm diameter of 40 mm diameter magnetic pot used for linear slide to machine assembly**

**Table 4. Power of magnetic pots steel housing machining**

| Operation name | Number of operations | Power (kW) | Time (min.) | Power (kWh) | Power (MJ) |
|---|---|---|---|---|---|
| Turning | 20 | 3 | 1.18 | 3.54 | 32.92 |
| Drilling | 10 | 3 | 0.82 | 2.46 | 22.88 |
| Turning | 10 | 3 | 0.74 | 7.41 | 68.91 |
| Turning | 20 | 3 | 1.18 | 3.54 | 32.92 |

**Energy (MJ) and $Co_2$ emissions (kg) are calculated based on conversion tables of Ref. [13]*

**Table 5. Theoretical power and $Co_2$ emissions of remanufacturing materials machining**

| Operation name | Number of operations | Power (kW) | Time (min.) | Power (kWh) | Energy (MJ) | $Co_2$ emissions (kg) |
|---|---|---|---|---|---|---|
| Drilling | 12 | 0.75 | 0.70 | 1.04 | 9.71 | 0.69 |
| Drilling | 12 | 0.75 | 0.52 | 0.39 | 3.60 | 0.26 |
| Drilling | 8 | 3 | 0.26 | 3.89 | 36.16 | 2.57 |
| Drilling | 8 | 0.75 | 0.21 | 0.16 | 1.45 | 0.10 |
| Drilling | 2 | 0.75 | 0.04 | 0.03 | 0.31 | 0.02 |
| Milling | 4 | 3 | 0.65 | 0.97 | 9.04 | 0.64 |
| Milling | 6 | 3 | 3.88 | 5.82 | 54.15 | 3.84 |
| Milling | 2 | 3 | 0.49 | 0.73 | 6.78 | 0.48 |
| Milling | 1 | 3 | 3.07 | 4.61 | 42.85 | 3.04 |
| Turning | 3 | 3 | 4.37 | 13.10 | 121.87 | 8.65 |

Input energy of primary manufacturing of N35 Neodymium disc of 70 mm diameter:-

= $IP_{PNM}$ x Weight of Neodymium disc (Table 8)

= 17.08 x 7.72 = 131.86 MJ (3)

Input energy of primary manufacturing of N35 Neodymium disc of 35 mm diameter=

= $IP_{PNM}$ x Weight of Neodymium disc (Table 8)

= 17.08 * 1.92 = 32.79 MJ (4)

$IP_{SC}$ = 11 MJ/kg

$IP_{SNM} = IP_{SC}$ x ECR = 11 x 0.854 = 9.39 MJ/kg (5)

Input energy of secondary manufacturing of N35 Neodymium disc of 35 mm diameter

= $IP_{SNM}$ x Weight of Neodymium disc (Table 8) = 9.39 x1.92 = 18.03 MJ- (6)

$O_{PCo2C}$ =1.6 kg/kg

$O_{PCO2NM}=O_{PCO2C}$ x ECR = 1.6 x 0.85 = 1.366 kg/kg (7)

Output $Co_2$ emission of primary manufacturing of N35 Neodymium disc of 70 mm diameter

= $O_{PCo2NM}$ x Weight of Neodymium disc (Table 8) = 1.366 x 7.72 = 10.55 kg (8)

Output $Co_2$ emission of primary manufacturing of N35 Neodymium disc of 35 mm diameter

= $O_{PCo2NM}$ x Weight of neodymium disc (Table 8) = 1.366 x 1.92 = 2.62 kg (9)

$O_{SCo2C}$ =0.83 kg/kg

$O_{SCo2NM} = O_{SCo2C}$ x ECR = 0.83 x 0.854 = 0.71 kg/kg (10)

Output $Co_2$ emission of secondary manufacturing of N35 Neodymium disc of 70 mm diameter

= $O_{SCo2NM}$ x Weight of Neodymium disc (Table 8) = 0.71 x 7.72 = 5.48 kg (11)

Output $Co_2$ emission of secondary manufacturing of N35 Neodymium disc of 35 mm diameter

= $O_{SCo2NM}$ x Weight of Neodymium disc (Table 8) = 0.71 x 1.92 = 1.36 kg (12)

$IP_{PS}$ = 28 MJ/kg

Input energy of primary manufacturing of steel housing of 90 mm diameter

= $IP_{PS}$ x Weight of steel housing (Table 8) = 28 x 18.35 = 513.8 MJ (13)

Input energy of primary manufacturing of steel housing of 40 mm diameter

= $IP_{PS}$ x Weight of steel housing (Table 8) = 28 x 12.75 = 357 MJ (14)

$IP_{SS}$= 18.2 MJ (Casting + Forming)

Input energy of secondary manufacturing of steel housing of 90 mm diameter

= $IP_{SS}$ x Weight of steel housing (Table 8) = 18.2 x 18.35 = 333.97 MJ (15)

Input energy of secondary manufacturing of steel housing of 40 mm diameter

= $IP_{SS}$ x Weight of steel housing (Table 8) = 18.2 x 12.75 = 232.1 MJ (16)

$O_{PCo2s}$ = 1.9 kg/kg

Output $Co_2$ emission of primary manufacturing of steel housing of 90 mm diameter

= $O_{PCo2s}$ x Weight of steel housing (Table 8) = 1.9 x 18.35 = 34.87 kg (17)

Output $Co_2$ emission of primary manufacturing of steel housing of 40 mm diameter

= $O_{PCo2s}$ x Weight of steel housing (Table 8) = 1.9 x 12.75 = 24.237 kg (18)

$O_{SCo2s}$ = 1.36 kg (Casting + Forming)
Output $Co_2$ emission of secondary manufacturing of steel housing of 90 mm diameter

= $O_{SCo2s}$ x Weight of Neodymium disc (Table 8) = 1.36 x 7.72 = 54.81 kg (19)

Output $Co_2$ emission of secondary manufacturing of steel housing of 40 mm diameter

= $O_{SCo2NM}$ x Weight of Neodymium disc (Table 8) = 1.36 x 1.92 = 13.63 kg (20)

Input energy and output $Co_2$ emissions of primary manufacturing of conventional machine tool:

$IP_{PC}$ = 20 MJ/kg

$W_{CMT}$ = 998 kg (Table 9)

$O_{PCo2C}$ =1.6 kg/kg [11]

$IP_{CMT} = IP_{PC} \times W_{CMT} = 20 \times 998 = 19960$ MJ (21)

$O_{PCo2\ CMT} = O_{PCo2C} \times W_{CMT} = 1.6 \times 998 = 1596.8$ kg (22)

Input energy and output $Co_2$ emissions of secondary manufacturing of conventional machine tool:-

$IP_{SC}$ = 11 MJ/kg

$W_{CMT}$ = 998 kg (Table 9)

$O_{SCO2C}$ =0.83 kg/kg

$IS_{CMT} = IP_{SC} \times W_{CMT} = 11 \times 998 = 10978$ MJ (23)

$O_{SCO2CMT} = O_{SCO2C} \times W_{CMT} = 0.83 \times 998 = 828.34$ kg (24)

Embodied energy and total $Co_2$ of conventional milling machine remanufacturing into CNC machine tool calculations:-

$P_E = IP_{TPRM\ (TABLE\ 5)} + IP_{TSRM\ (TABLE\ 6)} + IP_{TPCMT\ (EQ.\ (22))} + IP_{TSCMT\ (EQ.\ (24))} + IP_{TR\ (TABLES\ 3,\ 6,\ 7)}$
= 12411.36 + 2441.65 + 19960 + 10978 + 1584.10 = 47375.11 MJ (25)

$O_{T\ CO2} = O_{T\ CO2PRM\ (TABLE\ 5)} + O_{T\ CO2SRM\ (TABLE\ 6)} + O_{T\ CO2PCMT} + O_{T\ CO2\ SCMT} + O_{T\ CO2R\ (TABLES\ 6,\ 7)}$
= 838.92 + 205.68 +1596.8 + 828.34 + 113.70 = 3582.81 KG (26)

**Table 6. Input energy and output $Co_2$ emissions of primary manufacturing of materials and parts to fulfill eco-design and remanufacturing application**

| Part name | Material | Input material (kg) | Input power (MJ) | Output $Co_2$ emissions (kg) |
|---|---|---|---|---|
| Magnetic disc | Neodymium | 9.64 | 164.65 | 17.65 |
| Steel housing | Steel | 31.1 | 870.80 | 59.11 |
| Linear slide rail | Steel | 30.19 | 1026.38 | 63.40 |
| Linear slide carriage | Steel | 12.60 | 428.40 | 26.46 |
| Ball screw | Steel | 16.18 | 550.02 | 33.97 |
| Ball bearings | Steel | 7.70 | 261.80 | 161.70 |
| Guiding columns | Steel | 20.222 | 687.53 | 42.45 |
| Fixing plates | Steel | 13.540 | 460.36 | 28.06 |
| Holding pipes | Steel | 1.50 | 42 | 2.85 |

| Part name | Material | Input material (kg) | Input power (MJ) | Output $CO_2$ emissions (kg) |
|---|---|---|---|---|
| Holding screw M14 | Steel | 4.80 | 134.4 | 9.12 |
| Bearing flange | Aluminum | 2.543 | 559.46 | 33.06 |
| Z-axis ball screws holding plates | Aluminum | 12.96 | 2851.2 | 168.48 |
| Ball screws to knee holding plate | Aluminum | 11.448 | 2518.56 | 148.824 |
| Fixing plate | Aluminum | 1.89 | 415.8 | 24.57 |
| Pulley | Cast Iron | 12 | 1440 | 19.2 |

**Energy (MJ) and $Co_2$ emissions (kg) are calculated based on Metals eco-tables of Ref. [13]*

**Table 7. Input energy and output $Co_2$ emissions of secondary manufacturing of materials and parts to fulfill eco-design and remanufacturing application**

| Part name | Material | Input material (kg) | Input energy (MJ) | Output $Co_2$ emissions (kg) |
|---|---|---|---|---|
| Magnetic discs | Neodymium | 9.64 | 90.55 | 6.84 |
| Steel housing | Steel | 31.10 | 566.10 | 68.44 |
| Linear slide rail | Steel | 30.18 | 422.63 | 33.21 |
| Linear slide carriage | Steel | 12.60 | 176.40 | 13.86 |
| Ball screw | Steel | 16.17 | 138.22 | 10.86 |
| Ball bearings | Steel | 7.70 | 107.80 | 8.47 |
| Guiding columns | Steel | 20.22 | 283.11 | 22.24 |
| Fixing plates | Steel | 13.50 | 189.56 | 14.89 |
| Holding pipes | Steel | 1.50 | 27.30 | 2.04 |
| Holding screw M14 | Steel | 4.80 | 88.80 | 6.53 |
| Bearing flange | Aluminum | 2.54 | 17.29 | 0.585 |
| Z-axis ball screws holding plates | Aluminum | 12.96 | 88.13 | 2.98 |
| Ball screws to knee holding plates | Aluminum | 11.45 | 77.85 | 2.63 |
| Fixing plate | Aluminum | 1.89 | 35.91 | 2.15 |
| Pulley | Cast Iron | 12 | 132 | 9.96 |

**Energy (MJ) and $Co_2$ emissions (kg) are calculated based on Metals eco-tables of Ref. [13]*

**Table 8. Weights distribution of N35 neodymium magnetic pots**

| Part name | Number of sub-items | Total weight (kg) |
|---|---|---|
| N35 Neodymium disc of 70 mm diameter | 28 | 7.72 |
| Steel housing of 90 mm diameter | 14 | 18.35 |
| N35 Neodymium disc of 35 mm diameter | 38 | 1.92 |
| Steel housing of 40 mm diameter | 38 | 12.75 |

**Table 9. Weights distribution of conventional turret milling machine tool parts**

| Part name | Weight (kg) |
|---|---|
| Column | 544 |
| Knee | 136 |
| Turret | 36 |
| Ram | 136 |
| Saddle | 54 |
| Table | 92 |

## 4. RESULTS AND DISCUSSION

According to Anastasiia and Torgeir [8], Abullah et al. [9], manufacturing can be long term sustainable approach through closing the supply chain with remanufacturing to be triple-bottom lines of economic, environmental and social dimensions sustainability. Based on Fig. 13 economic viability of remanufacturing of conventional machine tool into conventional machine tool is consistent where the cost of rebuild four conventional Bridgeport milling machine is less than the cost of two new ones. In the same time, production capacities of four rebuilt machine is about the double of the one of two new milling machines. By application of remanufacturing to upgrade Bridgeport milling machine into CNC one by educational institutions, cost will be at its lower level due to sharing of resources and facilities between education and remanufacturing. Another economic criterion can be elicited through comparative literature based assessment. Time, power and cost consuming procedure of head rebuilding of convectional turret milling machine [14] can be eliminated through application of remanufacturing into CNC and following procedures can be removed:

(1). Quill and spindle removal.
(2). Quill and spindle inspection.
(3). Spindle and bearing removal.
(4). Spindle and bearing inspection.
(5). Spindle bearing reassembly/replacement.
(6). Pressing the bearings onto the spindle.
(7). Pressing the spindle into the quill.
(8). Pressing the upper spindle bearing into the quill.
(9). Re-Installing the quill assembly in the head.
(10). On machine spindle extraction.
(11). Feed driving gear assembly.
(12). Feed driving gear assembly removal.
(13). Feed driving gear assembly inspection.
(14). Feed driving gear assembly /reassembly.
(15). Feed reverse gear assembly.
(16). Feed reverse gear assembly removal.
(17). Drive housing removal.
(18). Drive housing inspection.
(19). Drive housing reassembly.

The above consuming procedures can be eliminated by introducing of CNC machine technology to control the cutting speed of the spindle by speed inventor automatically through the CNC controller and M-code instructions. This also required making the speed ratio of motor and spindle to be 1:1 through using double stage pulley of two diameters. One diameter is the same of the motor pulley to fulfill assembly through screws. The second diameter is the same as the spindle pulley diameter to fulfill speed transmission through belt at 1:1 ratio. This can satisfy controlling the cutting speed of the machine through CNC technology controlling. Fig. 9 can strengthen the viability of remanufacturing of conventional turret milling machine into CNC milling machine. Application of magnetic assembly based remanufacturing of machine tool based on educational institutions capabilities can find this approach more realistic through application of magnetic interfaces using. As show in Figs. 15 and 16, environmental viability is also consistent where high flexibility are supported with further reduction of power and $Co_2$ emissions through using of magnetic assembly remanufacturing comparing with traditional remanufacturing and buying new machine. Consequently, social viability will be satisfied based on economic and environmental viabilities where human employment, development and experience accumulation can be delivered through educational institutions.

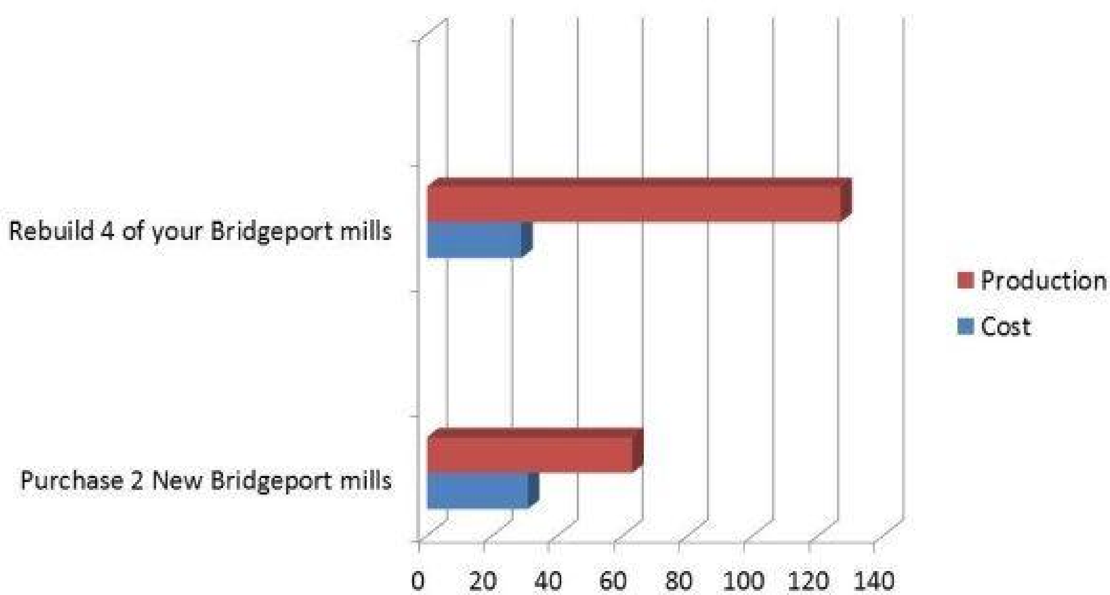


**Fig. 13. Economic viability of remanufacturing or rebuilding vs. buying new [14]**

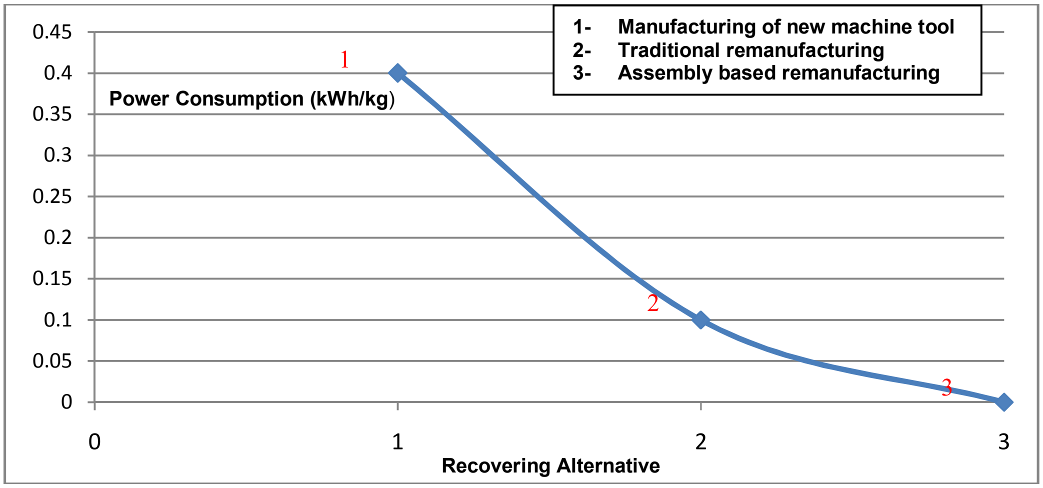


**Fig. 15. Power reduction through magnetic assembly, assembly based remanufacturing, comparative literature approach [7,10,13]**

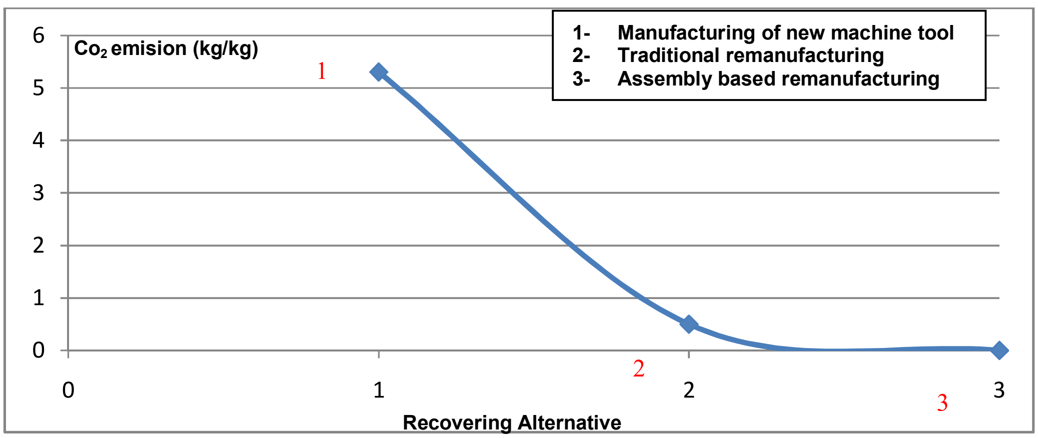


**Fig. 16. $Co_2$ emission reduction through magnetic assembly, assembly-based remanufacturing, comparative literature approach [7,10,13]**

The remanufactured end-of-life machine tools are studied to assess remanufacturability. Assessment is necessary to change barriers and difficulties of remanufacturing: Time consumption, effort consumption, power consumption, automation necessity, effect on remanufacturability and eco-design necessity. These criteria can express the practical feeling of lack in remanufacturability into differentiation expressions. Mixing of both theoretical considerations and remanufacturing application leads to discussion which can be exploited to propose conclusions that are the way to recommend:

(1). Research experience states that flexible fasteners technology is required to be adopted for viability of remanufacturing and fossil fuel and $Co_2$ emissions reductions. Magnetic pots can applied to facility substitution of slides and worn parts of conventional machine tools to moderate and update it into remanufactured CNC machine tool. Thus a huge mechanical work can be eliminated to save effort, power and time. Contact points can be added to be used to link modern CNC machine tool technology such as ball linear sides rails and carriages to conventional machine tool as a result of flexibility and modularity that are gotten by application of flexible fasteners for assembly based remanufacturing approach.

(2). Eco-design is required to increase remanufacturability and disassembly of end-of-life machine tool.

## 5. CONCLUSION

Literature of machine tool remanufacturing is in very nascent stage according to both of remanufacturing disciplines and industry of machine tool remanufacturing, which is in the stage of retrofitting and CNC machines technology adoption. While literature freezes machine tool remanufacturing in the feasibility stage. Consistency to remanufacturing literature show that localization of machine tool remanufacturing at feasibility stage generates inconsistency where a lot of remanufacturing disciplines are not satisfied by machine tool remanufacturing literature. Educational institutions can conduct remanufacturing and retrofitting of machine tool based on emerging technology where infrastructures of such educational institutes and student sustainable contribution can be exploited. Application of remanufacturing of machine tool based on educational institutions capabilities can lead to conclude the following:

(1). Eco-design idea is applied, since the machine design is compact Z-axis lead screw is substituted by two ball screw to be linked to both side of the machine column to right and left for facilitating uniform pulling and pushing forces of ball screws where Y-Z axes saddle is supported by two plates, upper and lower, the lower is linked to bottom of Y-Z axes saddle and the upper is linked at the top of the column of the machine.

(2). Linear guide ways of ball carriages can be assembled to machine tool core by using magnet pots that can assembly-disassembly by man power as flexible mechanical interface. This can eliminate the need for drilling and tapping of machine tool core to conduct the assembly by screws. This is a design for remanufacturing through increasing disassembly and reduction of power and related $Co_2$ emission for remanufacturing.

(3). Ball lead screws are used to replace frictional lead screws to reduce friction, backlash and lubrication using to conduct power reduction and $Co_2$ emissions as remanufacturing conscious environment. Nuts, keys and ball bearings and flanges are used to assembly the ball screw to core of machine tool.

(4). Accuracy is aimed and essential remanufacturing technology of machine tools are decided based on accuracy, emerging technology of open loop control system of CNC machine tools that can deliver consistent accuracy for application of daily life product manufacturing.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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