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Assessment of machine tool related environmental impacts for sustainable machining processes

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Abstract

In assessing the environmental impact or sustainability of machining processes and machined products, the characteristics of the machine tool should be considered. Difficulties in carrying out sustainability assessment include (1) collecting comprehensive input data, and (2) production and financial pressures preventing staff and machine availability to conduct in-depth analysis. Life cycle assessment reports are available for specific machine tools online, but these aren't commonplace. This research investigates how to conduct sustainability assessments on machine tools, with reference to prior research literature, international standards and a new machine tool market study. Science-based and cost-based approaches are considered. A cost-based top-down approach is relatively quick, can meet regulatory needs and would provide reasonably accurate 'bulk' results across numerous manufacturing processes and machines. However capturing and scientifically modelling details (bottom-up) of individual machines can drive identification and prioritisation of improvements and innovations to reduce environmental impact and meet future targets. Based on a market study of 120 numerical control (NC) machine tools in this research, cost-derived calculations did not accurately correlate to individual machine tools' sustainability metrics, due to reasons such as heterogeneity in the market. 55 different manufacturers were encountered in the study. Improved correlation represents an opportunity for future work. 15 years is a standard and commonly quoted value for the lifetime of a machine tool. Analysis of market data in this work indicated a machine tool life of double this value, around 30 years. From the study the average NC machine tool mass, volume and footprint dimension (length or width) were 6.6 metric tons, 23 m^3 and 2.8 m respectively. The monitoring of multiple sustainability-related metrics at high frequency on all machine tools would incur a high sensing and data management footprint, so a balance can be struck in terms of the assessment level, to maximise value-for-effort.

Keywords: Machine tools; environmental impact; assessment; machining; sustainability.

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1. Introduction

Nomenclature

EPD	environmental product declaration
GHG	greenhouse gas
LCA	life cycle assessment
NC	numerical control
TBL	triple bottom line

1.1. Background – sustainable manufacturing

This work begins with an introduction to the concepts of sustainability, environmental impact and the assessment of these for the case of manufacturing and machine tools.

Environmental sustainability is about eliminating the negative long-term impact of current human activities. In the words of the Brundtland Commission, 'Development that meets the needs of the present without compromising the

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ability of future generations to meet their own needs' [1]. Sustainable thinking can be applied to any activity to make it viable for the long-term. The three Pillars of Sustainability are the Economy, Environment and Society [2]. Health and safety (H&S) for workers falls under the Society pillar. The principles of sustainability include economic sustainability. In other words, traditional design and manufacturing and business principles are still valid, with new environmental principles running in parallel. These three pillars are referred to as the 'triple bottom line' (TBL). Only technologies which improve sustainability and circularity without negatively affecting process quality, process cost, flexibility and H&S are 'no brainers'. Most technologies must be weighed up to assess the associated trade-offs.

To explain what is meant by 'environmental impact', energy use and greenhouse gas (GHG) related carbon equivalent emissions are the most common examples in the review below, but all ISO 14040 [3] impact categories/ metrics such as land and water use are relevant. They can all be evaluated using a similar life cycle assessment (LCA) methodology.

Meanwhile, machine tools are best described as non-portable power tools used for cutting or shaping materials. In the case of this research the machine tools are numerically controlled (NC) 'subtractive processing' machines, for removing material. Figure 1 shows two examples of machine tools.

The environmental performance of manufacturing can be considered at different size scales or levels, including: (1) the global impact of manufacturing activity, for instance on the climate; (2) at the level of governments creating protective policies and legislation; (3) the level of individual manufacturing organisations; (4) concerning a manufactured product or product family; (5) at the manufacturing process level; and (6) at the individual machine level. This research mainly relates to (6), from the perspective of NC machining centres, although the thinking could be applied to other manufacturing equipment.

In terms of people who would want or need to assess the sustainability of a machine tool: these are mainly the product manufacturer who operates the machine tool, and the manufacturer who supplies the machine tool. In each case they wish to minimise environmental damage, but recognising the economic TBL pillar, the customer-supplier and company-investor relationships also play an important role.

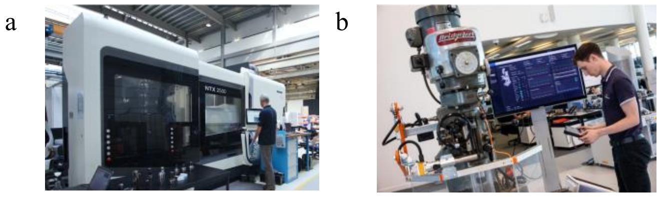

Fig. 1. Examples of machine tools: (a) larger and; (b) smaller exemplar.

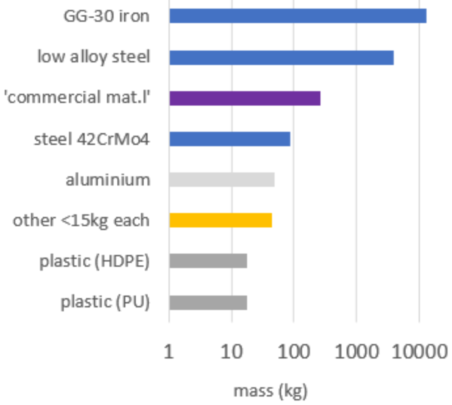

Fig. 2. Example of machine tool materials breakdown [17].

Manufacturers wish to offer future-friendly products to their customers, as well as meeting all other customer needs.

The main functions of sustainability assessment are as follows:

- Persuasion (to the market of superior technology, or to colleagues of the opportunity for improvement action);
- Direction, i.e. what improvement action to take;
- Convenience (acceptable scope regarding cost/ time), and;
- Evaluation with accuracy: results sufficiently close to the 'true' values, which can be iterated towards with increased investigative time and effort.

With these functions in mind and considering the open nature of environmental impact assessment for machine tools and machining processes, assessment should be designed to deliver a practical, informative and persuasive level of output to convey key information and support decision making.

1.2. Sustainability assessment and improvement

In 2025 it is mandatory for large European organisations to report on their carbon dioxide equivalent GHG emissions. The UK has streamlined energy and carbon reporting (SECR) [4], and the European Union has the corporate sustainability reporting directive (CSRD) and European sustainability reporting standards (ESRS) [5].

In reporting GHG emissions, the most widely recognised methodology is the Greenhouse Gas Protocol [6]. This methodology splits GHG emissions into three scopes. Scope 1 being the company's own activities, scope 2 is acquired electricity, steam, heat and cooling, and scope 3 is all upstream and downstream emissions in the value chain.

As organisations often lack access to each other's detailed operational data, scope 3 upstream carbon emissions are commonly calculated based on procurement data and the use of carbon conversion factors. Upstream emissions can be calculated based on the amount spent in each procurement category, combined with standard money-to-carbon conversion factors for the categories of purchased products. The ease of this cost-based approach can be understood, compared to the time and data access required to fully investigate supply chain resource flows and associated emissions.

The following sources consider how to evaluate sustainability performance for machine tools as independent systems.

ISO 14000 is a family of international standards for environmental management, which includes 'ISO 14955: Machine tools - Environmental evaluation of machine tools' [7]. ISO 14955 is focussed on design and evaluation of machine tools for energy efficiency, including how to take standardised measurements.

Krautzer et al. [8] created a software application for machine sustainability, to be used by small and medium manufacturers on various machine types. Manufacturers' feedback was that machine energy efficiency was important, they wanted to fulfil their legal requirements, they had little time available for environmental improvement activities and tools, and also they had little experience of LCA. The software application offered a rough and quick assessment of life cycle energy, then a detailed and more time-consuming energy assessment to follow: users appreciated this two-stage approach. The assessment could be completed in less than a working day. Users also appreciated the ability to characterise machines and identify improvement hotspots. The application could offer recommendations as per ISO 14955, to improve sustainability via energy efficiency. Denkena et al. [9] conducted a review of energy efficiency innovations for machine tools. These authors calculated that cutting machine tools account for 1 to 3 percent of global electricity demand. Machine design is discussed in terms of reducing power consumed by the machine's main and support units. Energy consumed by sub-components such as the spindle, linear drives and local exhaust ventilation (LEV, or extraction) system are considered. Recommendations include the use of minimum-level cooling strategies and intelligent non-cutting standby modes. Diaz et al. [10] focussed their environmental impact research on calculating machine electrical energy use based on the cutting rate. They proposed cutting tool changes to reduce consumption.

Uhlmann et al. [11] identified innovations for more sustainable machine tools. They discussed reconfigurable machine tools, constructed for exchangeable modules. Suggestions included machine down-sizing, better actuators, overcoming speed-related limits such as vibration, easy upgrades, and better process cooling. New sensor and control installation has been recommended to improve accuracy of older machines.

In the following research cases, the machine tool is a central element within a system or process under investigation for its sustainability.

Khan et al. [12] assessed TBL aspects including energy demand, cost and carbon emissions, to compare standard and emerging cooling and lubrication options assisting the turning of a titanium-based alloy. The authors used a radar chart/ spider diagram to visually compare the assessed TBL aspects. Sihag and Sandwan [13] included carbon emissions in a weighted TBL approach to calculate sustainability of a machining process, as a function of economic, environmental and social metrics. Hernandez et al. [14] proposed a TBL approach to sustainability evaluation for manufacturing, incorporating 6Rs (reduce, re-use, recycle, recover, remanufacture, redesign) and providing a machining case study. Salem et al. [15] also showcased a TBL approach to machining sustainability.

UN rule set [16], 'Machine-tools for drilling, boring or milling metal', is a set of product category rules (PCR) specifying information and the procedure and data requirements, to include in LCA and in a resulting environmental product declaration (EPD), to characterise a machine tool. The stated standard lifetime of a machine tool is 15 years. It is sometimes necessary for making calculations, to be able to assume product life without waiting years for a machine under test to fail. Also defined in the PCR are standard working daily hours and days per year, allowing standardised LCA of similar pieces of equipment.

An example EPD for a range of machine tools was produced by Grupo Nicholás Correa [17] with a supporting technical paper by Herrero et al. [18]. The contents provide interesting insights, such as the machine tool mass consisting of more than 90 % ferrous material for all models (see Figure 2). In the EPD there is an introduction, data are provided, then machines are assessed for life cycle environmental impact based on four impact categories in a 15-year use case. Herrero et al. show that for the four categories evaluated (global warming, photochemical oxidant formation, acidification and eutrophication), 80 % or more of the impact is associated with downstream activity, i.e. after the machine leaves the factory - mainly in its use phase.

Since the EPD [17] was released, few if any similar machine tool EPDs have been published. Potential reasons are:

- Machine manufacturers have diverse machine models and customer use phase profiles, so the cost and time to create and update EPDs presents a practical problem;
- Manufacturers do not wish to be compared or judged negatively on the environmental impact of their products;
- Confidentiality issues exist with accessing and publishing customers' usage profiles, as EPDs are supposed to be made publicly available;
- Lack of staff LCA skills and the required software licenses.

Recent research has aimed to optimise machining processes' environmental impact and sustainability. Researchers may focus on GHG emissions, whilst others have looked broadly at TBL-style sustainability metrics. For instance, changing the (i) process cutting fluid or (ii) cutting tool materials or (iii) workpiece condition of supply will affect not only those resources, but also impact on other resources such as consumption of electrical energy or the volume of cut material. Researchers use systems of equations to model and evaluate the potential impact of different technology options. Usually models take the specification of the machine tool into account, particularly modelling machine power consumption in response to machining parameters. All of the sustainability optimisation papers featured below include energy consumption as a metric. In TBL optimisation, the social and economic impact of technology changes are also taken into account quantitatively.

Li et al. [19] evaluated and minimised emissions for aluminium ball end milling, based on consumption of electricity and cutting tools, to optimise the milling tool path.

The researchers eliminated workpiece material and cut metal chips from their calculations: coolant/ lubricant was eliminated also as all cutting was done dry. Jia et al. [20] used multi-objective optimisation to simultaneously improve productivity, energy consumption and surface roughness in a steel milling process. Jiang et al. [21] presented a review of prior carbon emissions optimisation activity for machining. These authors created their own optimisation methodology which was tested on turning data. Salem et al. [15] pursued a TBL approach to sustainability assessment for machining processes, with normalised scoring and optimisation algorithms, presenting a case study to compare process cooling / lubrication technologies.

Machine tool manufacturing [22, 23, 24, 25] and computer-aided manufacturing [26] literature often focusses on productivity and cost improvements, but recent releases increasingly explain manufacturers' approach to sustainability. Improvements include energy-reducing machine technology, continuous improvement and ambitious targets, ISO14001 certification, faster more compact machines with more efficient subsystems, use of more recycled materials, reduction of annual manufacturing resource consumption and waste generation, and re-use of packaging. Computer-aided manufacturing software are available for crash and vibration (sources of hardware damage) avoidance, energy monitoring and for energy minimisation.

1.3. Knowledge gaps and motivation for study

A great deal of thought has already gone into assessing machine tools' sustainability and making them more sustainable. The importance of machine electrical energy efficiency is clear in the literature. Researchers may focus on one aspect of sustainability, whilst others may assess many metrics across environmental, economic and societal aspects. They use science-based approaches to model the sustainability of manufacturing machines and processes. Meanwhile manufacturers increasingly are compelled to report on their environmental impacts, where this is often calculated based on cost data due to the availability of those data.

To contribute usefully to the above situation, this work will investigate the following three questions. The machines themselves are the point of focus, rather than wider manufacturing processes.

(1) Firstly, how (and whether) a machine tool's cost can be used to estimate its sustainability metrics. Cost or value is the most easily obtained quantitative summarising variable, so this could be a means to assess machine tool sustainability. This study will investigate the relationship between sustainability metrics and cost, and the ability to quickly and simply predict these metrics.
(2) Secondly the work will investigate 15 years (from section 1.2) as a realistic age regarding machine tool life.
(3) Thirdly, the possible assessment levels of machine tool sustainability will be considered, trading off the ease of assessment against the value of what is delivered.

2. Investigative approach and metrics

To investigate the three questions posed, sources of recent and publicly available market data were required. Sources [27] and [28] were selected, providing access to multiple types of contemporary data on hundreds of machine tools. Price and top-level specification data were immediately available without logging in or making enquiries.

In analysing the above sources, machine cost was the main input or factor. Machine mass, dimensions and spindle power were the considered outputs, or responses. Arguably the cause-and-effect relationship is the other way round, e.g. a high machine mass increases its cost, but in this case cost is the most easily-obtained variable. The responses relate directly to resource consumption by the machine, and data on these three metrics were relatively easily available in the market data online. Furthermore, machine tool 'year of manufacture' data were gathered and analysed. The gathered data are reproduced in Appendix A for readers' benefit.

To address research questions 1 and 2 of section 1.3, two activity streams were carried out. The first addressed question 1, looking at the relationship between machine tool cost as the factor and machine mass, machine dimensions/ volume and spindle power as the responses, to see if cost could be simply used to infer the responses. For this activity data from source [27] were filtered for 30 lathes then for 30 milling machines, with the machine tool age controlled in a ±10 % range to mitigate the obvious influence of age on cost. The question 1 investigation imagines that for many machine tools within an organisation, the response data above are not immediately available, so it would be useful to infer these data for machine sustainability assessment.

To address question 2, the lifetime in service of machine tools en masse was tested empirically by looking at the frequency of sales for a further 60 machines against their year of manufacture, using the data source [28].

In all cases where external online data were used, results were filtered for machines in North America, creating a large pool of initial results. Machines filtered in were always in used but good working condition. A further filter was applied for completed sales made between January and July 2024. Only completed sales were surveyed, to validate that the machine cost was reasonable, i.e. a buyer had been found for that price and product description. Results were sorted by distance so that the order of displayed results was independent of cost. Results having missing response data were eliminated. No identifying information of transacting individuals or organisations was recorded.

3. Results

3.1. Machine sustainability metrics – question 1

The graph Figure 3 contains machine tool spindle power data versus cost, as extracted from [27] and collated in Tables A1 and A2. The data have been split with separate series for NC milling machines and lathes (turning). Y-axis data were converted to SI units for consistency. For the milling and turning series, lines of best fit have been applied with R^2 quoted. R^2 is a measure of variance, used as a goodness-of-fit measure for linear regression. A small R^2 indicates more spread of data points around (away from) the best fit curve.

The Figure 3 spindle power data points plotted versus cost form two 'triangles of uncertainty'. R^2 for milling machines is higher than for lathes at 0.4005. When NC machine tool mass and volume metrics from Tables A1 / A2 were plotted against cost in the same manner (not shown), the scatter of points was greater and R^2 was lower than for the case of spindle power.

In other words, prediction of these three machine sustainability-related metrics based on machine cost with a linear fit would yield quite inaccurate results for individual machines. The number of machines where the spindle power value was predicted by machine cost to within ±10 % tolerance, using the linear fit, was 13 out of 60 which is 22 %.

The patterns of machine metric data from Tables A1 and A2 show a trend of the three responses increasing with respect to cost. The majority of individual machine tool responses are not expected to be predictable to within (say) ±10 % based on machine cost. The implications of these findings for manufacturers are considered in section 4.1.

Some summarizing sustainability metric data of potential value are as follows: the average mass of the 60 NC machines surveyed from [27] was 6.6 metric tons, the average footprint dimension (length or width) was 2.8 m, and the average occupied volume was 23 m^3.

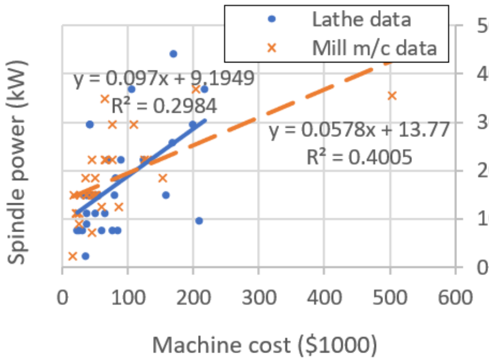

Fig. 3. Machine tool spindle power vs cost, from sales data.

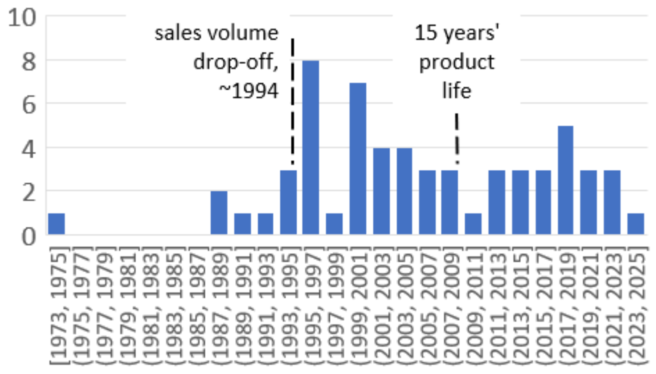

Fig. 4. Frequency by year of manufacture, 60 machine tools sold 2024.

3.2. Machine tool life – question 2

Figure 4 is a histogram from source data [28] as compiled into Table A3, of machine sales numbers versus their year of manufacture. The graph features dotted vertical lines denoting 15 years of machine life, i.e. the recommended standard (see section 1.2), and denoting the data-driven machine life.

The average year of manufacture of the 60 machines was 2006, meaning 18 years old (data collected in 2024). However average age does not indicate machine life in service, as the average machine in this analysis was still running well to the point of having been purchased. A better indicator of life was the point at which sales dropped off against the year of manufacture, with the assumption being that most machines beyond the drop-off age exceeded their life expectancy. They could no longer meet the filtered pre-condition of good working order, or perhaps desirability or compatibility, each of which cause product end of life. From Figure 4 the drop-off occurs between 1992 and 1996, which means approximately 30 years' life. Thus 30 years is the data-driven machine tool life.

4. Discussion and evaluation

4.1. General comments – questions 1 and 2

Commenting on question 1 (Figure 3 and Tables A1 and A2), there are several critical reasons why cost doesn't always correlate well to machine mass, size and power.

- For the used machines analysed, the amount of run hours and maintenance condition are variables of likely significance which are not controlled for here.
- A high-precision machining centre or a machine manufactured in a high cost-of-living country would cost more than average, for a given power/ mass/ size.
- Manufacturers have finite options for the sub-components which are available to use. There is likely to be discreteness in the spindle, pump and fan system power levels selectable for a given machining application.
- In general, there is heterogeneity of the marketplace in terms of machine manufacturers and countries of origin. 55 different manufacturers were identified in the market analysis.

Adding further factors as above, alongside techniques such as multivariate analysis and machine learning, could be an aspect for further research.

In terms of question 2, Figure 4 and machine tool lifetime, this study was not aligned to any manufacturing sector. It could be that precision machines last less years before they are unfit for purpose, whilst machines can go on making low-specification parts for longer. The evaluated 30 years could also be argued higher or lower based on the following.

- Higher: these market data do not include a 'hidden' body of machine tools never bought or sold after initial purchase, which have not experienced the potentially life-reducing process of disuse, decommissioning, logistics/ storage and recommissioning.

- Lower: these market data represent the conditions of manufacturing industry in recent decades. Current and future (2020s, 2030s) digital technology changes faster, thus there is a need for more flexible, shorter-lived machine tools which can be broken down or melted down and reconfigured then rebuilt more conveniently.

Notwithstanding the above it is considered that a study of 60 machines provides a useful and empirical machine life value, certainly compared to estimating without data.

Considering maintenance aspects, it should be assumed (ideally based on real data) that machine tool sub-elements such as the filters, oils, batteries, spindle, viewing windows, lights and sensors have a life which is shorter than the main structural elements of the machine such as the bed, table and chamber. Future work could focus on facts and figures on the subject of replacement parts.

4.2. Levels of sustainability assessment – question 3

Cost-related carbon emissions calculations are relatively quick and easy to do based on existing financial data, and can be done without modelling of industrial processes. This represents the 'top down' approach to meet regulatory reporting obligations, where most of the literature reviewed in section 1 takes the scientific 'bottom up' approach to sustainability assessment. The convenience of doing an assessment is partly related to the availability of different data types and the skill sets of staff in different organisational roles. Cost data are suitable to estimate scope 3 emissions for a large operation: to assess 'black box' supply chain activity which is outside an organisation's understanding. For a large organisation, even diverse variations in metrics and consumption level vs cost such as illustrated in Figure 3 can even out over many factories and machines.

On the other hand, there was no simple relationship found in this research for assessing individual machine tools' environmental impact accurately from their purchase cost. Manufacturing process owners can not 'follow the model' using cost data for sustainability improvement activity. Cost-based impact assessment mainly suggests spending less to lower the manufacturing environmental footprint. Manufacturers ideally need a tool which helps them to de-couple process emissions and process cost. For looking at a single manufacturing process or machine in-depth, machine sustainability metrics can be fairly easily available at a granular level via technicians or equipment suppliers. Direct investigation, measurement and science-based modelling can show the practical priorities and the means for improving sustainability. LCA and creation of EPDs are time-consuming and customer-specific as per section 1.2, and will be done where the demand requires it.

Table 1. Characterising levels of sustainability analysis for manufacturing organisations.

Level	Example	Pros	Cons
Very low	Aggregated within organisational-level carbon accounting.	Minimal investigation, use cost centre spend data. Bulk estimates work better on big data.	Indirect or estimated data- not insightful in terms of process improvement.
Low	Within internal improvement activity by a small manufacturer.	Continuous improvement, good for customers and morale.	Improvement (or not) may not be quantified.
Medium	Within improvement activity on large shop floor(s). Monitoring consumption at facility level.	Direct measurements. Quantified improvements. Develop staff specialisms.	Staff to juggle investigation time against their standard job role.
High	Includes dedicated staff, product LCA, and public release of detailed environmental performance data over time. Uses supply chain collaboration.	Show credentials. Should help win large orders (tendering). Easier for organisations to evaluate their macro footprint, meet their targets.	Time-consuming to carry out and requires specialist skills. Must allocate and retain staff. Organisations need to see return on time invested.
Very high	Continuous high-frequency monitoring of multiple sustainability metrics on all manufacturing equipment. Wireless devices and cloud data storage.	Intimate knowledge of processes. Gaining new insights. Useful for research and development use.	High storage, processing and management footprint. Includes maintenance and quality assurance for all monitoring sensors and electronics.

This brings the discussion to considering possible levels of environmental analysis and assessment for machine tools, which are ordered in Table 1 in terms of depth of analysis and time taken: from very low to very high. For most manufacturers the optimum level of environmental assessment is expected to be in the 'low to high' range from Table 1, but with large organisations tending towards 'high' due to economies of scale and the pressure from external regulation, customers and investors.

5. Conclusions

Assessment of environmental impact and sustainability is becoming a mandatory requirement for manufacturing organisations, with the greatest focus being on global warming (greenhouse gas emissions). In alignment with this, prior machine tool research emphasises machine energy efficiency. Furthermore, environmental performance improvement activity must be done with consideration of the critical economic and social factors also at play.

Environmental sustainability assessment can be done in ways which involve (a) process cost/ spend, or (b) process data and science-based model outputs.

The way in which to analyse environmental impact of machine tools was considered via a market study of 120 numerical control (NC) machine tools. It is suggested that spend-based environmental impact accounting provides bulk estimates of impacts valid at a large scale, but it will not provide accurate insight at the level of individual machines, unless further factors and modelling techniques are introduced - a future research opportunity. Basic predictions of machine tool sustainability metrics based on machine cost were not particularly accurate, for reasons such as heterogeneity in the market, with many machine designs and 55 manufacturers encountered within the study.

Option (a) above is quick and can be done at a higher level within an organisation to comply with regulations ('top-down'). Option (b) requires more effort and specialist knowledge, but by capturing details ('bottom-up') of machines and processes, it facilitates the identification and prioritisation of improvements and innovations, to reduce environmental impact and meet future targets.

15 years is a standardly used and commonly quoted lifetime for a machine tool. Analysis of machine market data in this work indicated a machine tool life of double this value, around 30 years.

From the market study, the average mass, volume and footprint dimension (length or width) of NC machine tools were 6.6 metric tons, 23 m^3 and 2.8 m respectively.

At the deep level of environmental analysis, the effort to monitor multiple metrics at high frequency on all machine tools incurs a high sensing and data management footprint. A balance can be struck between the extremes of assessment level and effort.

Acknowledgements

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Appendix A. Machine tool market data

Machine tool data were gathered and filtered from market sources [27] and [28], in the manner described in section 2. The filtered data are displayed in tables A1, A2 and A3. In tables A1 and A2, column 1 has been truncated for better overall readability.

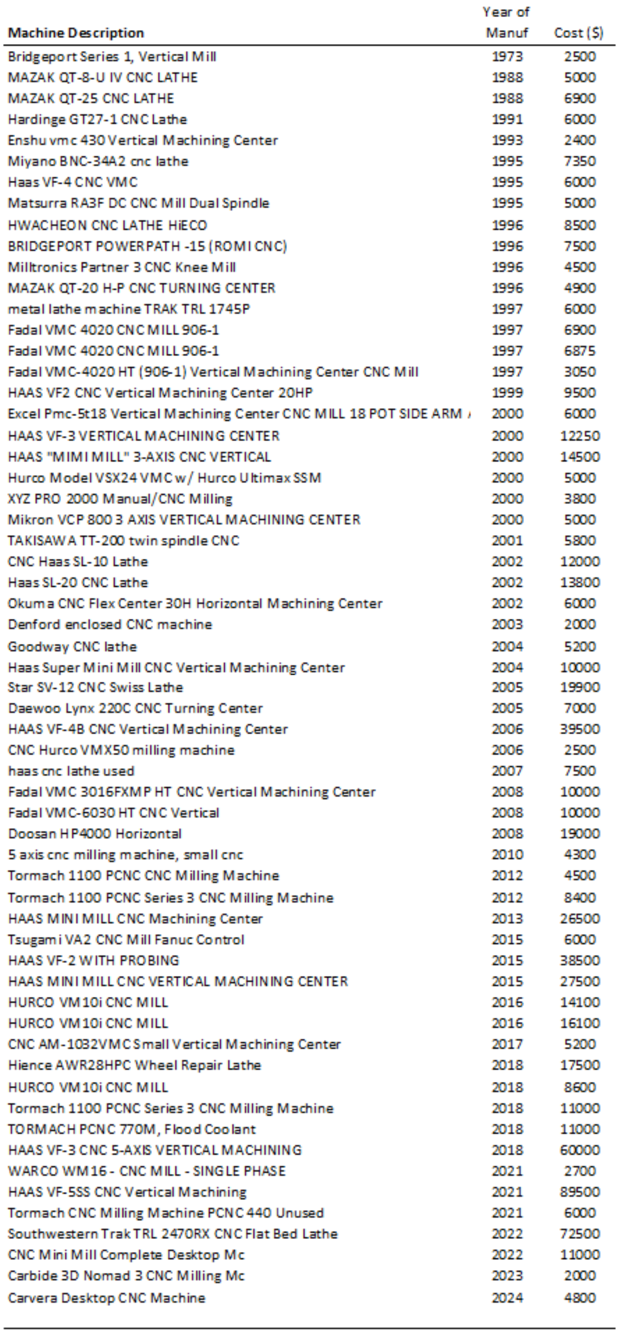
Table A1. 30 NC milling machines, manufactured 2012 to 2014, with metrics.

Description	Year	Price ($1000)	Spindle P (kW)	Largest dim (m)	Vol (m^3)	Mass (metric ton)
DOOSAN DNM400	2012	44	14.7	3.35	24.03	5.67
FEELER VMP580 CN	2012	24.5	11.0	2.74	10.16	2.72
HAAS VF5-50 CNC	2012	66	22.1	4.27	35.10	7.37
DOOSAN MYNX650	2012	131.5	22.1	3.35	28.04	9.00
HAAS EC1600 CNC	2012	126	22.1	4.39	48.24	14.15
HURCO VM20I CNC	2012	37	14.7	3.63	25.34	4.10
HAAS VF2 CNC Mill	2012	18.5	14.7	2.57	16.55	3.54
DMG MORI SEIKI N	2012	109	29.4	4.19	31.25	7.58
MAZAK VCN410A C	2012	35	18.4	2.81	14.54	4.91
HAAS DT1 CNC Mill	2012	20	11.0	2.54	12.85	2.34
HAAS VF2 CNC Mill	2012	38.5	14.7	2.57	16.55	3.54
HWACHEON VESTA	2013	44	14.7	3.35	28.03	7.26
DMG MORI SEIKI D	2013	49.5	18.4	2.79	14.19	3.90
MAZAK VCN510C-II	2013	152.5	18.4	2.87	23.23	6.89
HAAS VF2 CNC Mill	2013	52.5	14.7	2.57	16.55	3.54
JOHNFORD DMC21	2013	77	29.4	6.63	104.70	22.68
DMG MORI SEIKI D	2013	60.5	12.5	3.51	28.66	4.50
HAAS SUPER MINI	2013	23.5	11.0	2.54	13.12	2.31
AKIRA SEIKI PERFO	2014	25.5	8.8	2.39	11.00	3.22
HAAS VF2 CNC Mill	2014	44	22.1	2.57	16.55	3.54
BRIDGEPORT GX10	2014	27.5	14.7	2.95	17.09	5.89
BROTHER S700X1 C	2014	45	7.0	2.49	11.32	2.40
HAAS VF3SSYT CNC	2014	63.5	22.1	3.91	28.06	7.48
EMCO MAIER EMC	2014	86	12.5	2.92	18.65	4.31
SHW UNISPEED 6 C	2014	504	35.3	4.29	32.01	14.97
DOOSAN MYNX650	2014	77	22.1	3.35	30.37	11.34
HURCO VMX 30UH	2014	63.5	34.6	3.94	45.80	4.97
FERMAT WRF 130	2014	205	36.8	8.99	199.33	48.08
ACRA AM3 CNC Mil	2014	15.5	2.2	2.24	6.23	1.59
HAAS VF4 CNC Mill	2014	49.5	14.7	3.33	19.95	6.03

Table A2. 30 NC lathes, manufactured 2012 to 2014, with metrics.

Description	Year	Price ($1000)	Spindle P (kW)	Largest dim (m)	Vol (m^3)	Mass (metric ton)
GANESH CYCLONE	2012	60.5	7.4	2.57	9.00	3.63
MIYANO GN3200 C	2012	35.5	2.2	1.60	1.56	1.50
SWI 1840SX CNC La	2012	22	7.4	2.31	5.53	2.04
HAAS ST10Y CNC La	2012	64.5	11.0	2.44	6.51	3.58
HAAS ST20 CNC Lat	2012	33	14.7	3.63	19.40	4.08
KNUTH SINUS 330-	2012	24.5	7.4	3.20	6.24	2.69
OKUMA GENOS L4	2012	54.5	14.7	3.56	15.02	6.50
CHEVALIER FNL 25	2012	77	7.4	3.68	16.17	5.79
HAAS ST20 CNC Lat	2012	36.5	14.7	3.63	19.40	4.08
HAAS ST20 CNC Lat	2012	44	14.7	3.63	19.40	4.08
DOOSAN PUMA 40	2012	107.5	36.8	4.58	25.56	10.20
DOOSAN PUMA 21	2012	123.5	22.1	3.18	12.88	5.90
KITAKO HS4200N C	2013	157.5	14.7	3.12	19.36	6.80
HAAS TL1 CNC Lath	2013	37.5	8.8	2.13	6.20	1.95
JOHNFORD SL650C	2013	82.5	18.4	5.28	26.09	11.79
MAZAK QTN250-II	2013	168	25.7	2.92	9.50	5.22
HANWHA STL32H	2013	84	7.4	3.73	11.63	3.90
MAZAK QTS100S C	2013	38.5	11.0	1.91	5.15	3.50
DMG MORI SEIKI C	2013	169.5	44.1	4.90	25.05	12.02
DMG MORI SEIKI N	2013	80	14.7	3.96	15.53	5.44
HAAS TL2 CNC Lath	2013	30.5	7.4	2.82	10.72	2.68
DOOSAN LYNX 220	2013	38.5	14.7	2.57	6.88	3.49
TAKISAWA TCN 20	2014	49.5	11.0	1.73	3.07	3.39
TORNOS EVODECO	2014	209.5	9.6	2.58	12.35	3.80
HAAS ST30 CNC Lat	2014	42.5	29.4	4.34	24.72	6.49
HAAS DS30 CNC Lat	2014	69.5	22.1	4.34	24.72	5.53
MAZAK QTN350-II	2014	198.5	29.4	3.18	13.11	7.48
SAMSUNG SL40 CN	2014	88	22.1	5.00	23.49	9.30
DMG MORI SEIKI N	2014	218	36.8	6.17	39.02	14.06
HAAS ST30 CNC Lat	2014	42	29.4	4.34	24.72	6.49

Table A3. 60 NC machines. All sold in 2024, sorted by year of manufacture.



Machine Description	Year of Manuf	Cost ($)
Bridgeport Series 1, Vertical Mill	1973	2500
MAZAK QT-8-U IV CNC LATHE	1988	5000
MAZAK QT-25 CNC LATHE	1988	6900
Hardinge GT27-1 CNC Lathe	1991	6000
Enshu vmc 430 Vertical Machining Center	1993	2400
Miyano BNC-34A2 cnc lathe	1995	7350
Haas VF-4 CNC VMC	1995	6000
Matsurra RA3F DC CNC Mill Dual Spindle	1995	5000
HWACHEON CNC LATHE HiECO	1996	8500
BRIDGEPORT POWERPATH -15 (ROMI CNC)	1996	7500
Milltronics Partner 3 CNC Knee Mill	1996	4500
MAZAK QT-20 H-P CNC TURNING CENTER	1996	4900
metal lathe machine TRAK TRL 1745P	1997	6000
Fadal VMC 4020 CNC MILL 906-1	1997	6900
Fadal VMC 4020 CNC MILL 906-1	1997	6875
Fadal VMC-4020 HT (906-1) Vertical Machining Center CNC Mill	1997	3050
HAAS VF2 CNC Vertical Machining Center 20HP	1999	9500
Excel Pmc-5t18 Vertical Machining Center CNC MILL 18 POT SIDE ARM	2000	6000
HAAS VF-3 VERTICAL MACHINING CENTER	2000	12250
HAAS "MIMI MILL" 3-AXIS CNC VERTICAL	2000	14500
Hurco Model VSX24 VMC w/ Hurco Ultimax SSM	2000	5000
XYZ PRO 2000 Manual/CNC Milling	2000	3800
Mikron VCP 800 3 AXIS VERTICAL MACHINING CENTER	2000	5000
TAKISAWA TT-200 twin spindle CNC	2001	5800
CNC Haas SL-10 Lathe	2002	12000
Haas SL-20 CNC Lathe	2002	13800
Okuma CNC Flex Center 30H Horizontal Machining Center	2002	6000
Denford enclosed CNC machine	2003	2000
Goodway CNC lathe	2004	5200
Haas Super Mini Mill CNC Vertical Machining Center	2004	10000
Star SV-12 CNC Swiss Lathe	2005	19900
Daewoo Lynx 220C CNC Turning Center	2005	7000
HAAS VF-4B CNC Vertical Machining Center	2006	39500
CNC Hurco VMX50 milling machine	2006	2500
haas cnc lathe used	2007	7500
Fadal VMC 3016FXMP HT CNC Vertical Machining Center	2008	10000
Fadal VMC-6030 HT CNC Vertical	2008	10000
Doosan HP4000 Horizontal	2008	19000
5 axis cnc milling machine, small cnc	2010	4300
Tormach 1100 PCNC CNC Milling Machine	2012	4500
Tormach 1100 PCNC Series 3 CNC Milling Machine	2012	8400
HAAS MINI MILL CNC Machining Center	2013	26500
Tsugami VA2 CNC Mill Fanuc Control	2015	6000
HAAS VF-2 WITH PROBING	2015	38500
HAAS MINI MILL CNC VERTICAL MACHINING CENTER	2015	27500
HURCO VM10i CNC MILL	2016	14100
HURCO VM10i CNC MILL	2016	16100
CNC AM-1032VMC Small Vertical Machining Center	2017	5200
Hience AWR28HPC Wheel Repair Lathe	2018	17500
HURCO VM10i CNC MILL	2018	8600
Tormach 1100 PCNC Series 3 CNC Milling Machine	2018	11000
TORMACH PCNC 770M, Flood Coolant	2018	11000
HAAS VF-3 CNC 5-AXIS VERTICAL MACHINING	2018	60000
WARCO WM16 - CNC MILL - SINGLE PHASE	2021	2700
HAAS VF-5SS CNC Vertical Machining	2021	89500
Tormach CNC Milling Machine PCNC 440 Unused	2021	6000
Southwestern Trak TRL 2470RX CNC Flat Bed Lathe	2022	72500
CNC Mini Mill Complete Desktop Mc	2022	11000
Carbide 3D Nomad 3 CNC Milling Mc	2023	2000
Carvera Desktop CNC Machine	2024	4800

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