Machine-Specific Estimation of Milling Energy Consumption in Detailed Design

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Devarajan Ramanujan
Technical University of Denmark

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Till Boettjer, Johan Thoft Krogshave
Mechanical Engineering Section
Department of Engineering
Aarhus University
Aarhus C, Denmark 8000

Devarajan Ramanujan*
Mechanical Engineering Section, Department of Engineering
Center for Digitalization, Big Data, and Data Analytics
Aarhus University
Aarhus C, Denmark 8000

ABSTRACT

Manufacturing is a significant contributor to global greenhouse gas emissions and there is an urgent need to reduce the energy consumption of production processes. An important step towards this goal is proactively estimating process energy consumption at the detailed design stage. This is a challenging task as variabilities in factors such as process specifications, machine tool architecture, and workpiece geometry can significantly reduce the accuracy of the estimated energy consumption. This paper discusses a methodology for machine-specific energy estimation in milling processes at the detailed design stage based on the unit process life cycle inventory (UPLCI) model. We develop an adjusted UPLCI model that includes adjustment factors for uncertainties in machine tool specifications and the specific cutting energy of a workpiece material. These adjustment factors are calculated through experimental measurement of energy consumption for a reference test part on a specific machine tool. To validate the adjusted UPLCI model, we conducted a case study that measured the energy consumption for machining three parts made of Aluminum 6082 on two separate three-axis vertical milling machines, a Chevalier QP2040-L and a Leadwell MCV-OP. Results show that the UPLCI model consistently overestimated the total energy consumption for machining the three validation parts across both machine tools. We also found the adjusted UPLCI model significantly reduced the estimation errors for the same tests for both machine tools.

NOMENCLATURE

$\overline{K}_*$	Mean value of adjustment factor for energy consumption in mode $*$
$\overline{K}_{idle,s}$	Mean value of adjustment factor for energy consumption in idle mode for state s
$\overline{K}_{milling,o}$	Mean value of adjustment factor for energy consumption in milling mode for operation o
$\sigma^2_{K_*}$	Variance in adjustment factor for mode $*$
$E^{a-uplci}_{total}$	Total energy consumption estimated using the adjusted UPLCI model
$E^{real}_{*,i}$	Measured energy consumption in mode $*$ for experimental run i
E^{uplci}_{*}	Energy consumption in mode $*$ estimated using the UPLCI model
E^{uplci}_{total}	Total energy consumption estimated using the UPLCI model
N	Total number of experimental runs
$P^{real}_{*,i}$	Measured power consumption in mode $*$ for experimental run i
P^{uplci}_{*}	Power consumption in mode $*$ estimated using the UPLCI model
$t^{real}_{*,i}$	Measured time in mode $*$ for experimental run i

*Address all correspondence devr@eng.au.dk

t_*^{uplci}	Time in mode $*$ estimated using the UPLCI model
$E_{milling,o}^{uplci}$	Energy consumption in milling mode for operation o estimated using the UPLCI model
SCE	Specific cutting energy
VRR	Volume removal rate

1 INTRODUCTION

The manufacturing sector is among the significant contributors to global greenhouse gas emissions. In 2014, manufacturing and construction industries accounted for approximately 20% of the global carbon dioxide emissions [1]. Reducing resource consumption of manufacturing processes amidst the increasing global demand for products is a challenge that needs to be addressed by all industries [2]. Accurate estimation and minimization of energy and resource consumption in manufacturing processes at the detailed design and process planning stages are important steps towards this goal [3, 4]. This facilitates process parameter selection and product redesign before significant manufacturing resources are committed. A notable research effort in this regard is the $CO_2PE!$ unit process life cycle inventory (UPLCI) framework [5]. This framework describes a consistent methodology for collecting, documenting, and providing life cycle inventory for unit manufacturing processes. It can also be used to estimate the potential for environmental improvements in various machine tools. A total of 31 unit manufacturing processes (incl. material reducing processes such as milling, drilling, boring, turning, and grinding) have been modeled using the UPLCI framework [6]. Developing reliable life cycle inventory models for manufacturing processes such as milling is challenging as machining operations are complex and their performance depends on multiple inter-related process parameters and physical phenomena [7].

Our paper presents a methodology for machine-specific energy estimation based on the UPLCI milling model developed by Kalla et al. [8]. We develop an adjusted UPLCI milling model that reduces uncertainties in milling energy estimation due to variations in machine tool specification and specific cutting energy of workpiece materials. The original UPLCI milling model [8] uses a combination of empirical measurements and physics-based first principles in order to create a generalized methodology that is applicable across a variety of materials and machine tools. Managing uncertainties due to empirical measurements, material and energy-dependence on machine setups is a significant challenge in such models [9]. For example, empirical data used in the UPLCI milling model (e.g., specific cutting energy for a material, and the time for milling specific features) have been compiled from a broad range of previous literature. Moreover, the UPLCI model does not account for machine tool-specific discrepancies (e.g., planned versus actual time taken to machine a feature). Consequently, there is significant uncertainty in estimating energy consumption in a milling process, given a specific workpiece material and machine tool. This makes it challenging to utilize the UPLCI model to estimate material and machine tool-specific energy consumption in milling processes at the detailed design stage.

Figure 1 provides an overview of the idea proposed in this paper. As shown, a machine-specific, adjusted UPLCI model is derived from the UPLCI milling model in order to better estimate the energy consumption from milling parts on a specific machine tool. The primary contribution of our paper is the methodology presented for deriving an adjusted UPLCI model that can reduce uncertainties in estimating manufacturing process life cycle inventory data. Our approach is primarily intended for legacy machine tools without embedded digital technologies that can collect life cycle inventory data (e.g.,component-level energy consumption) directly from the controller. We validate the proposed methodology by comparing the milling energy consumption estimated using the UPLCI model and the adjusted UPLCI model with corresponding experimentally measured values. Results show that the adjusted UPLCI model enables a more accurate estimation of milling energy consumption for a given setup. Therefore, results from our work can improve the integration of the UPLCI methodology into standard data models [10] and tools linking manufacturing process planning data and life cycle assessment [11, 12, 13].

2 BACKGROUND

Estimating the resource consumption in manufacturing processes during the detailed design stage is vital step for reducing manufacturing-related impacts [4]. The $CO_2PE!$ unit process lifecycle inventory (UPLCI) framework [5] was one of the first research works aimed at creating a systematic methodology for parametric estimation of manufacturing energy consumption (and other life cycle inventory) for unit manufacturing processes. By relating life cycle inventory to process parameters, this methodology facilitates proactive estimation of process resource consumption at the detailed design stage. In the $CO_2PE!$ methodology information of life cycle inventory is collected using separate approaches, a screening approach and an in-depth approach. The advantage of the UPLCI framework is that it presents a formalized, reusable methodology for collecting, documenting, and using life cycle inventory models for various unit manufacturing processes. This is especially useful when estimating energy and resource consumption for complex products and assemblies produced using multiple unit processes. Previous research has developed UPLCI models for a variety of manufacturing processes such as milling, drilling, boring, turning, and grinding [6].

This section provides a brief overview of the energy estimation process in the UPLCI milling model. A more detailed description of this model, including an example detailing the application of the model can be found in Kalla et al. [8]. As shown in Fig. 2, the UPLCI milling model identifies three distinct power levels for a generic machine tool based on its operation mode: P^{uplci}_{basic}, P^{uplci}_{idle}, and $P^{uplci}_{machining}$.

- P^{uplci}_{basic} corresponds to the power demand resulting from peripherals and auxiliary components when the machine tool is in 'stand-by' mode. This power demand is present from the time the machine tool is started until the time it is turned off (t^{uplci}_{basic}).
- P^{uplci}_{idle} corresponds to the power demand from the machine tool in the 'run-time' mode for generating movement of the tool relative to the workpiece. This power demand is present from time 'move start' until time 'move stop' as shown in Fig. 2 (t^{uplci}_{idle}).
- $P^{uplci}_{machining}$ corresponds to the power demand resulting from physical cutting of the workpiece in the 'milling' mode. This power demand is present from time 'milling on' until time 'milling stop' as shown in Fig. 2 ($t^{uplci}_{milling}$).

The total energy consumption for the milling process is the sum of the energy consumption for the three operation modes, as shown in Eqs. 1 & 2.

$$E^{uplci}_{total} = E^{uplci}_{basic} + E^{uplci}_{idle} + E^{uplci}_{milling} \tag{1}$$

$$= P^{uplci}_{basic} \cdot t^{uplci}_{basic} + P^{uplci}_{idle} \cdot t^{uplci}_{idle} + P^{uplci}_{milling} \cdot t^{uplci}_{milling} \tag{2}$$

In the UPLCI model, $t^{uplci}_{milling}$ and $P^{uplci}_{milling}$ are calculated as shown in Eqs. 3 & 4 respectively.

$$t^{uplci}_{milling} = \frac{Length \quad of \quad cut}{feed \quad rate} \tag{3}$$

$$P^{uplci}_{milling} = VRR \cdot SCE \tag{4}$$

In Eq. 3, the length of cut is estimated based on the geometry of the workpiece and is summed over all all milling operations. A more detailed description of the procedure for estimating milling times can be found in Kalla et al. [8]. In Eq. 4, the VRR for a milling operation is calculated from the set feed rate, the width of cut, and depth of cut. The SCE for different workpiece materials has been compiled from secondary sources in the UPLCI milling model. In reality, SCE varies with VRR [14]. Therefore, the UPLCI milling model provides average SCE values based on recommended feed rates and cutting speeds for a specific material.

P^{uplci}_{idle} is estimated using the power demand from energy consuming peripherals (e.g., spindle motors, axes motors, coolant pumps, tool changer, etc.) present in the machine tool. This information is usually available in the manufacturer provided specifications for a machine tool. While no specific guidelines are provided, Kalla et al. [8] calculate P^{uplci}_{idle} by summing a fraction of the rated power of the axes motors, a fraction of the rated power consumption of the spindle motor, and the power consumption of peripherals with relatively constant power demand (e.g., coolant pump). Estimating the above fraction requires users to have relevant expertise or information on the specific machine tools being analyzed. The idle time (t^{uplci}_{idle}) is calculated using Eq. 5.

$$t^{uplci}_{idle} = t^{uplci}_{milling} + t^{uplci}_{handling} \tag{5}$$

Here, $t^{uplci}_{handling}$ refers to the the total time during which the tool is moving relative to the workpiece without making any physical contact. Therefore it includes the time for re-positioning the tool from the home position to the approach point, approach and overtravel time, as well as the tool retraction time.

P^{uplci}_{basic} is also estimated as a fraction of the maximum power draw of the machine tool as per the manufacturer's specifications. t^{uplci}_{basic} is estimated as shown in Eq. 6.

$$t^{uplci}_{basic} = t^{uplci}_{milling} + t^{uplci}_{handling} + t^{uplci}_{load/unload} \tag{6}$$

Here, $t_{load/unload}^{uplci}$ refers to the time taken for clamping and unclamping the workpiece as well as cleaning the machine tool between jobs. Loading and unloading times are determined based on the weight of a workpiece and the type of clamping device [15].

Table 1 details the relationships between uncertainties in machine tool specification, workpiece properties, and the corresponding terms in the UPLCI milling model. As shown, the terms P_{basic}, P_{idle} only depend on uncertainties in machine tool specification while $P_{milling}$ also depends on uncertainties in workpiece properties. For terms related to time, $t_{handling}$ only depends on uncertainties in machine tool specification while $t_{load/unload}$ and $t_{milling}$ also depends on uncertainties in workpiece properties. Therefore, all energy consumption terms in the UPLCI model ($E_{basic}, E_{idle}, E_{milling}$) are influenced by uncertainties in machine tool specifications as well as workpiece properties.

3 METHODOLOGY

This section details the methodology for constructing the adjusted UPLCI model that is based on the UPLCI milling model described in the background section. Given a specific workpiece material and machine tool, the proposed approach for constructing the adjusted UPLCI model involves the following steps.

1. Measuring the basic, idle, and milling energy consumption as well as time for a reference test part. A set of 'N' experimental runs are performed by varying the feed rate and cutting speed for milling various features in the reference test part (within permissible limits of the machine tool).
2. Comparing the experimental energy consumption and time data with those estimated from the UPLCI milling model. Results from these comparisons are used to compute adjustment factors for the adjusted UPLCI milling model.
3. Experimental validation of the adjusted UPLCI model using parts with the same material and approximately similar dimensions as the reference test part.

The following subsections explain these three steps in further detail.

3.1 Measuring experimental energy consumption and time for a reference test part

Figure 3 shows the reference test part used for developing the adjusted UPLCI model. This part was originally developed by the Japanese Standards Association (JSA) and it has been used in previous studies on milling power consumption [16,17]. Features in the part are machined in the following order: face milling (F1,1-3), three large grooves and three small grooves (F2,1-6), three pockets, oriented along the X-axis, Y-axis, and 45°(F3), trochoidal groove (F4) , and six holes (F5).

Figure 4 describes the procedure for measuring the basic, idle, and milling power consumption for the reference test part. For each experimental run ($i : 1 \rightarrow N$), the product of the basic power ($P_{basic,i}^{real}$) and the basic time ($t_{basic,i}^{real}$) is used to compute the basic energy consumption. $P_{basic,i}^{real}$ is recorded when the machine is in stand-by mode. $t_{basic,i}^{real}$ is the time elapsed from loading the workpiece until it is unloaded from the machine.

The idle time (t_{idle}^{real}) is estimated as the total time taken for execution of the numerical control (NC) code for the air cut which includes the time for milling, re-positioning the tool/workpiece, and tool changes. The idle energy ($E_{idle,i}^{real}$) is estimated by summing power consumption over the duration of idle time for the air cut (see Figure 4). We separate the overall idle energy consumption into different states (e.g., tool change, rapid traversal, etc.), based on the hypothesis that variation in power consumption between the states significantly contributes to estimation errors in the UPLCI milling model. Further details on these states are provided in Sec. 3.2.

In order to compute milling energy consumption ($E_{milling,i}^{real}$), the power consumption for the air cut is subtracted from the power consumption for the part cut. Integrating the resulting data over the time for executing the NC code gives $E_{milling,i}^{real}$. The milling time ($t_{milling,i}^{real}$) is estimated by calculating the duration for which the difference in power consumption for machining and air cut is greater than zero. This procedure was adopted over directly measuring the milling time as we did not have access to the machine tool controller or experimental apparatus for accurately detecting when the tool was in contact with the workpiece. In the proposed model, we separate the milling energy consumption and times based on the operations used in machining the various features in the reference test part (F1-F5). This results from our hypothesis that variations in SCE and milling time for machining different features result in significantly different predictions errors in the UPLCI model. Further details are provided in Sec. 3.2.

3.2 Computing adjustment factors

To construct the adjusted UPLCI model, we define three adjustment factors ($\overline{K}_{basic}, \overline{K}_{idle,s}, \overline{K}_{milling,o}$) that account for uncertainties in material properties and machine tool specifications. $\overline{K}_{basic}$ is the mean value of the adjustment factor for basic energy consumption. The adjustment factor for idle energy consumption ($\overline{K}_{idle,s}$) is split into factors specific to each idle state (s). The set of states (S) accounted in the current work, includes idle material removal (MR), idle non-material removal (NMR), rapid traverse (RT), and tool change (TC). Here, MR and NMR refer to the states corresponding to the energy consumption for moving the tool relative to the workpiece, while removing material (e.g., active cutting), and not removing material (e.g., overtravel) respectively. Please note that the UPLCI milling model described in Sec. 2 does not distinguish between different idle states. Therefore, $E_{idle,s}^{uplci}$ for a specific idle state is calculated as the product of the overall idle power (P_{idle}^{uplci}) and the estimated time for that specific state ($t_{idle,s}^{uplci}$). The adjustment factor for milling is separated into factors ($\overline{K}_{milling,o}$) based on the different types of operations (o) that are used to create specific features on the part. Please note that the UPLCI model does not distinguish between such milling operations. Therefore, $E_{milling,o}^{uplci}$ for a process o is calculated as the product of the overall milling power $P_{milling}^{uplci}$ and the estimated time for the specific operation $t_{milling,o}^{uplci}$. The set of operations (O) accounted in the current work only include those defined in the reference test part; face milling, groove milling, pocketing, trochoidal milling, and drilling. The UPLCI estimates for drilled features was estimated based on previous work by Kellens et al. [18]. The machining power for each hole is estimated as the product of the specific cutting energy and the volume removal rate, similar to the UPLCI milling model. Drilling time for a hole of depth d is estimated as $d/(f \times S)$. Here, f is the linear tool feed and S is the rotational speed of the drill.

Based on the above definitions, the adjusted UPLCI model used for estimating total energy consumption in milling processes is defined as shown in Eq. 7.

$$E_{total}^{a-uplci} = \overline{K}_{basic} \cdot E_{basic}^{uplci} + \sum_{s \in S} \overline{K}_{idle,s} \cdot E_{idle,s}^{uplci} + \sum_{o \in O} \overline{K}_{milling,o} \cdot E_{milling,o}^{uplci} \tag{7}$$

The adjustment factors $\overline{K}_{basic}, \overline{K}_{idle,s}, \overline{K}_{milling,o}$ are computed by comparing the actual energy consumption and times for the reference test part against those estimated by the UPLCI model. This ratio is averaged over a set of ‘N’ experiments involving the machining of the reference test part with varying process parameters. Please note that the adjustment factor specific to a milled feature (e.g., F2 in Fig. 3) is averaged over all repeated features in the reference test part. The adjustment factor for any mode ($*$) is computed as shown in Eq. 8. The uncertainty in estimating of the adjustment factor is represented by the variance in the factor over the ‘N’ experimental runs, as shown in Eq. 9.

$$\overline{K}_{*} = \frac{\sum_{i=1}^{N} \frac{E_{*,i}^{real}}{E_{*,i}^{uplci}}}{N} \tag{8}$$

$$\sigma_{K_*}^2 = \frac{\sum_{i=1}^{N} \left(\frac{E_{*,i}^{real}}{E_{*,i}^{uplci}} - \overline{K}_{*} \right)^2}{N} \tag{9}$$

3.3 Experimental validation of the adjusted UPLCI model

The adjusted UPLCI model is validated by comparing the estimated basic, idle, and milling energy consumption against the corresponding experimental energy consumption for three validation parts. The procedure for measuring the times and energy consumption for the validation parts is identical to that used for reference test part (see Sec. 3.1). Estimates from the adjusted UPLCI model are compared against those from the UPLCI milling model (described in Sec. 2) in order to quantify the improvement in estimating the basic, idle, and milling energy consumption.

The three validation parts (VP1,2,3) used in this process are shown in Fig. 5. Each validation part contains at least two different features and collectively cover the different features in the reference test part. A trochoidally milled groove was omitted from the validation part due to the challenges in accurately measuring the idle and machining time for this operation. Features in VP1 are machined in the following order: face milling (F1), groove (F2), two pockets (F3), and three holes (F3). VP2 includes: face milling (F1), one circular pocket (F2), and eight holes (F3). VP3 includes: face milling (F1), groove (F2), four pockets (F3), and one hole (F4). All validation parts have the same material as the reference test part. The dimensions of the blank workpiece are identical for all validation parts and the reference test part.

4 CASE STUDY

We implemented the methodology described in Sec. 3 to develop an adjusted UPLCI model for two 3-axis vertical milling machine tools, the Chevalier QP2040-L (MT1) and the Leadwell MCV-OP (MT2). Both machine includes a control panel, an automatic tool changer, and a cutting fluid pump. The manufacturer-provided specifications for MT1 can be downloaded from the following link: https://tinyurl.com/chevalierQP2040-L. The specifications for MT2 were gathered from a physical handbook.

An SCT013-000 hall effect current sensor was used to measure the apparent power consumption at the main supply line for MT1 and MT2. As both machines used 3-phase AC power, apparent power consumption was computed as the product of the root mean square value of the measured current (400 samples per cycle) and a fixed supply voltage of 230 V. The current measurement was made on a single phase as the system was assumed to be well balanced. An Arduino Due was to process the current sensor data and output them to a laptop computer. The SCT013-000 current sensor has a measurement range of 0-100 Amperes and an output range of 0-50 mA with a non linearity of +/- 3%. The measurement uncertainty for the current sensor used for this study was $\pm$ 8.5 % in the measurement range of 0-100 A [19].

A total of 8 reference test parts (RP1,2...8) were machined on both machine tools with varying process parameters. All parts were made of Aluminum 6082 and were geometrically identical. Four combinations of spindle speeds and feed rates were used on each machine tool to machine the reference test parts (low-low, high-high, low-high and high-low). Please note that MT1 & MT2 have different values for achievable spindle speeds and feed rates. Thus, the respective process parameters used for machining the parts on MT2 were lower than MT1 (see Appendix Tbl. 7).

Two pairs of parts (RP1&5, RP2&6,...) were machined with identical process parameters on each machine tool. The facing operations were performed by a 50 mm face mill with 5 inserts on MT1 and by a 50 mm face mill with 4 inserts on MT2. End-milling operations were performed by three different end mills (6, 8 and 10 mm) all with 4 inserts. Drilling operations were performed using a 4 mm drill with 2 inserts. Table 2 summarizes the cutting tools used in the case study. Table 7 in the Appendix lists the process parameters used for milling the reference test parts and validation parts for both machine tools. The routing plan for the machining all reference test parts is shown in the Appendix Fig. 8. Three layers of face-milling, 2 layers groove milling and pocketing, and 1 layer of trochoidal milling were preformed along with 6 drilling operations. The experimental data from machining the 8 reference test parts were compared to estimates from the UPLCI model in order to compute the corresponding adjustment factors (see Sec. 3.2) and develop the adjusted UPLCI model specific for the two machine tools. Analysis of the trochoidal milling operation on MT1 showed it was difficult to separate the collected energy consumption data into idle and milling energy. This is due to the varying width of cut and small time period of contact between the tool and the workpiece. Therefore, trochoidal milling was not performed on MT2 and these data are also not reported for MT1.

The three validation parts (see Sec. 3.3) were also machined on the same machine tools. All three validation parts were made of the same material as the reference test part. Facing operations for all validation parts also used a 50 mm face mill. End-milling operations used a 4 mm end mill with 4 inserts as well in addition to the end mills used for machining the reference test parts. Drilling operations were performed using a 6 mm drill with 2 inserts. The routing plan for the machining all validation parts is shown in the Appendix Fig. 9.

A safety distance of 1 mm and a rapid feed rate of 15000 mm/min was used for all parts in the case study. A stationary parallel holding vice was used to clamp all reference test parts and validation parts. All workpieces were manually handled by the operator. The loading process included clamping the workpiece, and closing the machine door. Unloading included opening the machine door, cleaning, and unclamping of the workpiece. The average time for loading and unloading for all parts was 19.6 seconds.

To validate the adjusted UPLCI model, estimates from the UPLCI milling model and the adjusted UPLCI model were compared with experimental measurements from machining the three validation parts. Section 5 presents the results from these analyses. Please note that the assumptions made for estimating energy consumption using the UPLCI model are listed in the Appendix.

5 RESULTS

5.1 Machining reference test parts

Figure 6 shows the results for basic, idle, and milling energy consumption for machining the reference test parts on machine tools MT1 (top) and MT2 (bottom). As shown, these results were compared to the corresponding estimates from the UPLCI model. When computing the energy consumption for the various states, we found that some measurements were anomalous since the automatic spindle lubrication system was powering on during the milling or air cut operations. As milling power is computed by subtracting the energy consumption of the part cut and the air cut, this power draw would have been incorrectly attributed to the milling power for such operations. Consequently, the milling power could not be accurately estimated in such instances. Therefore, the results presented in this paper exclude these anomalous data points. For MT1, the following number of observation were excluded: face milling (2/24), groove milling (7/48), pocketing (6/24), and drilling (14/48). The results for MT2 exclude the following number of anomalous data points for each operation: face milling (8/24), groove milling (15/48), pocketing (12/24), and drilling (32/48).

5.1.1 Milling energy consumption

The UPLCI estimates for milling energy consumption are independent of the process parameters (feed rate and spindle speed) and equivalent for machining all eight reference test parts. Thus, the energy consumption data for milling a specific feature across all reference test parts are grouped according to their mean value. Results show that the UPLCI model was reasonably accurate in estimating milling energy consumption across the features on the reference test parts. The minimum and maximum nominal estimation errors for milling energy consumption per feature on MT1 were 2.6% (F1) and 60.0% (F2) respectively. For MT2, these values were 7.4% (F3) and 91.3% (F2,1-3) respectively. Here, nominal error is estimated as percentage difference between E_*^{uplci} and the nominal value of E_*^{real}. For MT1 and MT2 the milling energy consumption was ~11% and ~9% of the overall energy consumption respectively. Thus, the milling energy consumption was relatively small when compared to energy consumption in the idle and basic modes.

5.1.2 Idle energy consumption

Figure 6 also shows the mean energy consumption of the different idle states (MR, NMR, RT, TC) for machining of the reference test parts on MT1 and MT2. The UPLCI model showed reasonable accuracy in estimating the energy for RT. The UPLCI model had considerable errors in estimating the idle energy consumption during MR, NMR, and TC. Please note that as shown in Fig. 6, energy consumption in NMR, RT, and TC are significantly lower than in MR. Therefore the largest contributor to error in estimating idle energy consumption results from the error in estimating energy consumption in MR. The UPLCI model estimated idle power consumption as 9673.1 W for MT1 and 4853.6 W for MT2 (see Appendix Tbl. 6). The above estimates differed considerably from the measured average power consumption in RT, MR, NMR, & TC as shown in Tbl. 5. The mean value for idle time (for all eight reference test parts) was 6.32 minutes for MT1 and 8.64 minutes for MT2. However, the idle time estimated using the UPLCI model was 5.42 minutes for MT1 and 5.22 minutes for MT2.

5.1.3 Basic energy consumption

With regards to basic energy consumption, the minimum and maximum nominal estimation errors for the UPLCI model were 277.5% (RP7) and 353.9% (RP5) for MT1 as well as 430.8% (RP6) and 837.2% (RP5) for MT2 respectively. The basic power consumption estimated by the UPLCI model was 3750.0 W for both MT1 and MT2 (see Appendix Tbl. 6). This was significantly higher than the experimentally measured value of 814.0 W for MT1 and 970.0 W for MT2. Results also show that the basic power varied across the experiments. For MT1, the variation in basic power was between 745.0 W to 926.0 W. The basic power level of MT2 varied between 403.0 W and 626.0 W. Apart from the errors in estimating basic power, errors in estimating the idle time and loading/unloading time contributed to an increased error in estimating basic energy consumption as per the UPLCI model. The UPLCI model underestimated the basic time with an average of 2.4 minutes (12.9 %) for MT1 and 32.6 seconds (9.8 %) for MT2. The significant errors in estimating idle and basic energy consumption result in a large error in estimating the total energy consumption. This is due to the fact that collectively, the idle and basic energy consumption represented ~89% and ~91% of the overall energy consumption for milling the reference test parts on MT1 and MT2 respectively .

5.2 Calculation of adjustment factors

Table 3 lists the mean value and variance for the adjustment factors computed for developing the adjusted UPLCI model. The equations for computing these factors are listed in Sec. 3.2. In Tbl. 3, a value for $\overline{K_*}$ close to 1 indicates that the values estimated from the UPLCI model was the same as nominal value from the experimental measurement. A value for $\overline{K_*} < 1$ indicates the UPLCI model overestimated the energy consumption for that specific mode and vice versa. As shown in Tbl. 3, the UPLCI model significantly overestimated the energy consumption in the idle and basic mode for both MT1 and MT2. The values of $\overline{K}_{milling,o}$ in Tbl. 3 indicate that the UPLCI model was reasonably accurate in estimating energy consumption of face milling, groove milling, pocketing, and drilling. For both MT1 & MT2, the UPLCI model significantly overestimated the energy consumption of the idle mode during MR, NMR, and TC, while the energy consumption during RT was underestimated.

5.3 Machining of validation parts

Table 4 details the results from machining the three validation parts (VP1, VP2, VP3) on MT1 and MT2 respectively. Experimental measurements for energy consumption in each mode are compared to those estimated using the UPLCI model and the adjusted UPLCI model. As shown, the UPLCI model significantly overestimated the idle and basic energy consumption for all three validation parts for both MT1 & MT2. The sources of estimation error for the validation parts was similar to those observed for the reference test parts.

For MT1, the average values for the measured idle power consumption were 748.6 W for VP1, 709.1 W for VP2, and 734.9 W for VP3. However, the idle power estimated by the UPLCI model was 9673.1 W. Similarly, the basic power consumption estimated by the UPLCI model was significantly more than the experimentally measured average of 770.0 W.

In the case of MT2, value for the measured idle power consumption was 396.3 W fro VP1, 464.5 W for VP2, and 546.6 W for VP3. However, the idle power consumption was estimated to be 4854.0 W in the UPLCI model. Similarly, the basic power consumption estimated by the UPLCI model was significantly more than the experimentally measured average of 1006.2 W for MT2. As shown in Tbl. 4 the UPLCI model significantly overestimated the total energy consumption for all three validation parts for both machine tools.

The adjusted UPLCI model was developed using the adjustment factors listed in Tbl. 3. As shown in Tbl. 4, the adjusted UPLCI model significantly reduced the errors in estimating energy consumption in the idle and basic modes. The maximum nominal estimation error for idle energy consumption was for MT1 and MT2 were 25% (VP2) and 49% (VP2) respectively. The maximum nominal estimation error for basic energy consumption was for MT1 and MT2 were 27% (VP3) and 68% (VP1) respectively. With regards to milling energy consumption, the maximum estimation error was 16% (VP2) and 37% (VP1) for MT1 and MT2 respectively. Thus, the adjusted UPLCI model significantly reduced the estimation error for idle, basic, and milling energy consumption for all the validation parts in the across both machine tools. This translates to an increased accuracy in estimating the total energy consumption for the validation parts when compated the original UPLCI model, as detailed in Tbl. 4.

6 DISCUSSIONS

6.1 Results estimated using the UPLCI model

In the UPLCI model, theoretical milling energy is estimated from the removed material volume due to machining of part features and the SCE of the workpiece material. Thus, according to the UPLCI model, the estimated milling energy per feature is equivalent for machining the same parts on MT1 and MT2. This estimation is also independent of any selected process parameters. However, experimental measurements demonstrated that the milling energy consumption varied significantly between the two machine tools for all parts. Furthermore, changing the process parameters on a specific machine tool also resulted in a change in milling energy consumption, as in reality, SCE is a function of VRR [14]. We also found the UPLCI model results in underestimation of the milling time due to combination of, (i) simplifying the tool path, (ii) not considering the age and wear of the machine tool (and feed drives, bearing etc.) that can influence the achieved feed rates compared to the planned feed rates of the machining process. Additionally, the UPLCI model does not consider the wear level of work tools. Using a worn work tool increases the power consumption in a machining process [20] which would imply the UPLCI model underestimates milling power consumption. In practice, the SCE assumed in the UPLCI model dictates the accuracy of the estimated milling power consumption. When viewing the milling energy consumption at the feature level, we found that that the UPLCI model did not establish a consistent pattern. The accuracy of the UPLCI model for estimating feature level milling energy consumption depends on several interrelated factors such as feature type, feature geometry, process parameters, and machine tool specifications.

The method used in the UPLCI model for calculating idle power consumption (see Appendix Tbl. 6) significantly overestimated the idle power for both machine tools. While experienced UPLCI practitioners may estimate these values more accurately, the lack of a clear methodology to do so is a challenge, especially for legacy machine tools. We also found that changes in process parameters significantly changed the power consumption in the idle state, as reflected in previous literature [21]. However, the method used in the UPLCI model for calculating idle power consumption does not account for such variations. Furthermore, while the UPLCI model did not differentiate between various states in the idle mode (MR, NMR, RT, and TC), experimental results showed a significant difference in idle power consumption between these states. The idle power consumption in each state was also dependant on the architecture of the specific machine tool as shown in Tbl. 5. The average idle power draw for machining the reference test parts was higher for MT1 in each state in the idle mode, as it had larger sized actuators. Even so, the difference in overall idle power consumption between MT1 and MT2 was 1.25 kW against 5 kW estimated by the UPLCI model. Results also showed that the UPLCI model also had significant errors in estimating the idle time. There were several reasons for the observed errors. The UPLCI model does not consider acceleration periods of the feed drives during rapid traversal. Also, in short traversals the set traversal rate might not be reached thus increasing the time spent in rapid traversal. The travel length estimate of the UPLCI model also simplifies the actual toolpath which caused a variation between the travel time estimated using the UPLCI model compared to the experiments. Finally, the time for tool change also depends on the position of the tool in the magazine. In summary, we found several potential reasons for the UPLCI model overestimating idle power consumption and underestimating idle time. Even so, the total idle energy consumption was consistently overestimated by the UPLCI model which indicates the influence of underestimating idle time was low.

The UPLCI model estimates the basic power consumption based on the rated power of the machine tools. However, as indicated by our experimental results, the measured basic power consumption was significantly lower. Furthermore, we observed there was a noticeable variation in basic power consumption across the experiments. The UPLCI model also underestimated the basic time. To illustrate, the average measured basic times for machining the reference test parts was 378 seconds for MT1 compared to 448 seconds for MT2. The UPLCI model estimated these basic times as 329 seconds and 396 seconds respectively. The underestimation in basic time worked against the overestimation of basic power and reduced the overall error in estimating basic energy consumption. Even so, the UPLCI model significantly overestimated the basic energy consumption for both MT1 and MT2.

6.2 Results estimated using the adjusted UPLCI model

Results show the adjusted UPLCI model reduced the errors for estimating basic, idle, and milling energy consumption for all three validation parts across both MT1 and MT2, when compared to the original UPLCI model. The need for a machine-specific UPLCI model is further highlighted by the difference in milling energy consumption of MT1 and MT2 the validation parts. The original UPLCI model estimates milling energy consumption purely based on the geometry of the part and the workpiece material. However, as shown in Tbl. 4, the used machine tool significantly affects the milling energy consumption. The minimum and maximum and difference in the nominal values of milling energy consumption (between MT1 and MT2) were 13.8 kJ and 1.5 kJ for VP1 and VP3 respectively. Table 4 also shows that the adjusted UPLCI model was generally more accurate in estimating the energy consumption for MT1 when compared to MT2. A significant reason for this, was the difference in condition of the two machine tools. MT1 was a newer machine that was primarily used in an academic environment whereas MT2 had seen prolonged use in a production environment. This is also reflected in the variance values for the adjustment factors detailed in Tbl. 3. When compared to MT1, the larger variance values for MT2 across almost all adjustment factors, indicates that it had lower precision in energy consumption when machining the reference test parts.

While the adjusted UPLCI model significantly improved the accuracy in estimating energy consumption for the validation parts when compared to the original UPLCI model, results show there is significant room for improvement. Figure 7, details the significant factors contributing to uncertainties that reduce the accuracy of the total energy consumption estimated using the adjusted UPLCI model. These factors were identified by the authors based on assumptions made in the process of constructing the adjusted UPLCI model and experimental results from machining the reference test parts and the validation parts. The adjusted UPLCI model partially compensates for these uncertainties shown in Fig. 7 through the computed adjustment factors for milling operations. However, the accuracy of these compensations is limited by the uncertainty in the described factors. Estimating the sensitivity of the total energy consumption to uncertainty in these factors is outside the scope of the current work and requires further research.

7 CONCLUSIONS & FUTURE WORK

This paper developed an adjusted UPLCI model that enabled machine-specific energy estimation in milling processes using the UPLCI model. We discussed a methodology to compute adjustment factors for the adjusted UPLCI model that accounts for uncertainties in machine tool specifications and the specific cutting energy of a workpiece material. We conducted a case study that demonstrated the development of the adjusted UPLCI model via experimental measurements of energy consumption for a reference test part. The adjusted UPLCI model was validated using experimental measurements of energy consumption for three different parts. Results showed that the adjusted UPLCI model significantly reduced errors in estimation idle, basic, and milling energy consumption, when compared to the UPLCI model. Thus, the adjusted UPLCI model finds application in cases where manufacturers utilize specific machine tool(s) to produce different components. In such cases, the increased accuracy of the proposed adjusted UPLCI model enables better comparative analysis between components, and and re-adjusting the estimation over time (e.g. in order to account for degradation of the machine tool).

Findings from this study point to the need for further research and discussions on the following aspects.

- The adjusted UPLCI model significantly reduced estimation errors for idle, basic, and milling energy consumption compared to the UPLCI model. Even so, there is significant room for improving its accuracy. A potential opportunity in this regard is the development of a standard milling test that improves the generalization of the adjustment factors in the adjusted UPLCI model. We found different designs for test parts have been used in previous research [17, 22]. These parts are primarily designed to capture variability in milling energy consumption resulting from a variability in the type of milling operation (e.g., face milling, pocketing). In order to improve the estimation energy consumption using the adjusted UPLCI model, a standard test case should also include standards for non-cutting operations (e.g., tool changes, rapid tool traversals, etc.)
- Improving the estimation of basic and idle power consumption requires a more fine-grained understanding of power consuming peripherals in the machine tool. For example, the procedure for measuring machine tool energy consumption detailed in Behrendt et al. [17] can be potentially used to develop a more accurate component-wise energy consumption model within the adjusted UPLCI model.
- There is a need for accurately estimating the idle time and milling time for features with complex toolpaths (e.g., trochoidal groove) in order to improve the adjusted UPLCI model. This is a trivial task in cases where there is access to the CNC controller. However, in these cases, the ability to temporally associate power consumption with a specific operating mode of the machine tool opens the possibility of applying more complex energy estimation methods [23]. In

cases such as ours, that involve legacy machine tools and proprietary controllers, there is a potential for using low-cost sensors setups [24] for automated estimation of idle time and milling times.

- Future in-depth studies should separately examine estimation errors and correction factors for power consumption and times in the various modes. Results from such studies could suggest specific focus areas for improving the formulation of the adjusted UPLCI model.
- Our current work focuses on estimating Scope 1 process energy consumption, i.e., energy consumed within a production facility, in detailed design. A more holistic approach for mitigating environmental impacts of machining energy consumption requires future work that also considers impacts from energy sources external to the production facility (Scope 2) and embodied energy of materials and chemicals used in the production process (Scope 3) [25].

Acknowledgements

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Table 1: Potential sources of uncertainties in the UPLCI model for estimating milling energy consumption.

Terms in UPLCI milling model	Uncertainty in machine tool specifications	Uncertainty in workpiece properties
P_{basic}	Power draw of machine tool in stand-by mode	
P_{idle}	Power draw of machine tool in run-time mode	
$P_{milling}$	Realized material removal rate	Specific cutting energy of workpiece material
$t_{handling}$	Realized cutter traversal rate	
$t_{load/unload}$	Accessibility of work area, clamping, and cleaning method	Workpiece dimensions and geometric complexity
$t_{milling}$	Realized feed per tooth and cutting speed	Geometric complexity of milled feature

Table 2: Work tools used in the case study for both machine tools MT1 & MT2. The tools include, face mills (FM), end mills (EM1-EM4), and drills (D1,D2). The same set of end mills and drills were used for operations on MT1 & MT2. The operations (F1-5) performed by each work tool are shown for the reference test part and the three validation parts.

Tool		Diameter [mm]	Teeth	Tip angle	Operation in part: RP	VP1	VP2	VP3
Face mill	FM (MT1)	50	5		F1	F1	F1	F1
	FM (MT2)	50	4		F1	F1	F1	F1
End mill	EM1	10	4		F2	F2		F2
	EM2	8	4		F4			
	EM3	6	4		F2, F3	F3	F2	F3
	EM4	4	4					F2
Drill	D1	6	2	140^o			F3	F4
	D2	4	2	140^o	F5	F4		

Table 3: Mean and variance values for adjustment factors in the adjusted UPLCI model for MT1 and MT2.

	MT1		MT2	
Milling operation (o)	$\overline{K}_{milling,o}$	$\sigma^2_{K_{milling,o}}$	$\overline{K}_{milling,o}$	$\sigma^2_{K_{milling,o}}$
Face milling	1.05	0.02	0.80	0.08
Groove milling	0.64	0.01	0.64	0.07
Pocketing	0.91	0.04	0.93	0.18
Trochoidal groove milling	-	-	-	-
Drilling	1.19	0.04	3.69	0.86
Idle State (s)	$\overline{K}_{idle,s}$	$\sigma^2_{K_{idle,s}}$	$\overline{K}_{idle,s}$	$\sigma^2_{K_{idle,s}}$
MR	0.05	0.000046	0.06	0.0011
NMR	0.02	0.000005	0.03	0.0002
RT	1.54	0.02	3.18	0.4
TC	0.20	0.01	0.14	0.0008
Mode ($*$)	$\overline{K}_*$	$\sigma^2_{K_*}$	$\overline{K}_*$	$\sigma^2_{K_*}$
Basic	0.24	0.00023	0.15	0.0009

Table 4: Comparison of measured energy consumption for a specific mode with corresponding estimates using the UPLCI model and the adjusted UPLCI model. Results are shown for all three validation parts (VP1, VP2, VP3). Errors in the values for measured energy consumption are due to measurement uncertainties. Standard errors in the estimates from the adjusted UPLCI model are shown in the table. Nominal errors are computed using the nominal value of the measured energy consumption and the nominal value of the corresponding estimate.

MT1						
		Measured [kJ]	UPLCI [kJ]	Nominal error UPLCI [%]	adjusted UPLCI [kJ]	Nominal error adjusted UPLCI [%]
VP1	Milling	57.3 ± 4.9	83.2	45	61.9 ± 1.6	8
	Idle	141.9 ± 12.1	1523.7	974	130.1 ± 0.2	8
	Basic	211.0 ± 17.9	664.0	215	156.1 ± 17.8	26
	Total	410.2 ± 34.9	2270.9	454	348.1 ± 11.2	15
VP2	Milling	34.2 ± 2.9	40.5	19	39.6 ± 1.0	16
	Idle	90.9 ± 7.7	1256.1	1282	88.6 ± 0.2	3
	Basic	148.9 ± 12.7	560.2	276	131.7± 15.0	12
	Total	274.0 ± 23.3	1856.9	578	259.9 ± 8.4	0.3
VP3	Milling	53.3 ± 4.5	79.1	48	61.3 ± 1.6	15
	Idle	373.3 ± 31.7	3968.9	963	280.7 ± 0.5	25
	Basic	515.6 ± 43.8	1611.9	213	379.0 ± 43.1	27
	Total	942.1 ± 80.1	5659.9	501	720.9 ± 23.2	24

MT2						
		Measured [kJ]	UPLCI [kJ]	Nominal error UPLCI [%]	adjusted UPLCI [kJ]	Nominal error adjusted UPLCI [%]
VP1	Milling	43.5 ± 3.7	83.2	91	59.5 ± 10.2	37
	Idle	117.7 ± 10.0	764.5	549	84.8 ± 23.2	28
	Basic	322.0 ± 27.4	664.0	106	101.9 ± 1.1	68
	Total	483.2 ± 41.1	1511.7	212	246.2.3 ± 38.9	49
VP2	Milling	30.4 ± 2.6	40.5	33	39.9 ± 6.9	31
	Idle	97.4 ± 8.3	630.3	547	49.4 ± 13.5	49
	Basic	245.2 ± 20.8	560.3	128	85.9 ± 0.9	65
	Total	372.9 ± 31.7	1231.1	230	175.3 ± 27.7	53
VP3	Milling	51.8 ± 4.4	79.1	52	58.7 ± 10.1	13
	Idle	288.2 ± 24.5	1991.4	590	181.1 ± 49.7	37
	Basic	519.5 ± 44.2	1611.9	210	247.4 ± 2.6	52
	Total	859.6 ± 73.1	3682.4	328	487.2 ± 76.9	43

Table 5: Average values of measured power consumption in the different states of the idle mode for MT1 and MT2 while machining the reference test parts.

Idle state	MT1 [W]	MT2 [W]
MR	451.5	266.2
NMR	763.7	589.6
RT	517.3	397.2
TC	1011.0	236.5

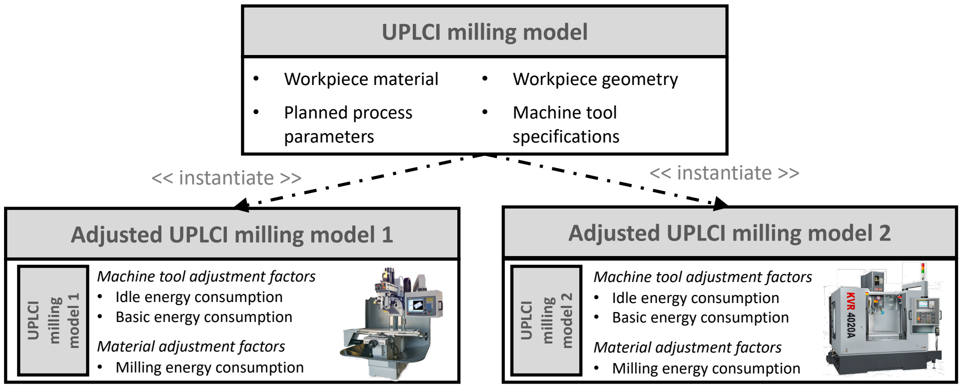

Fig. 1: The adjusted UPLCI milling model for a given process context is generated as an instance of the UPLCI model with material and machine tool-specific adjustment factors for the respective machine modes.

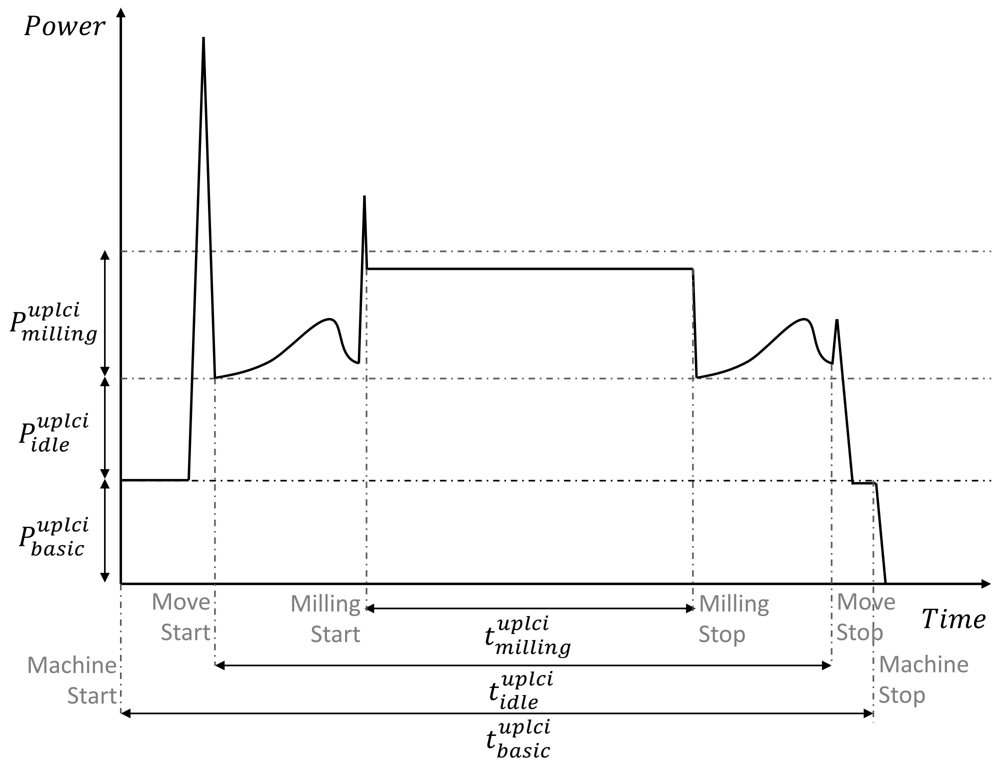

Fig. 2: Power consumption for a generic milling process as detailed by the UPLCI model. Adapted from Kalla et al. [8].

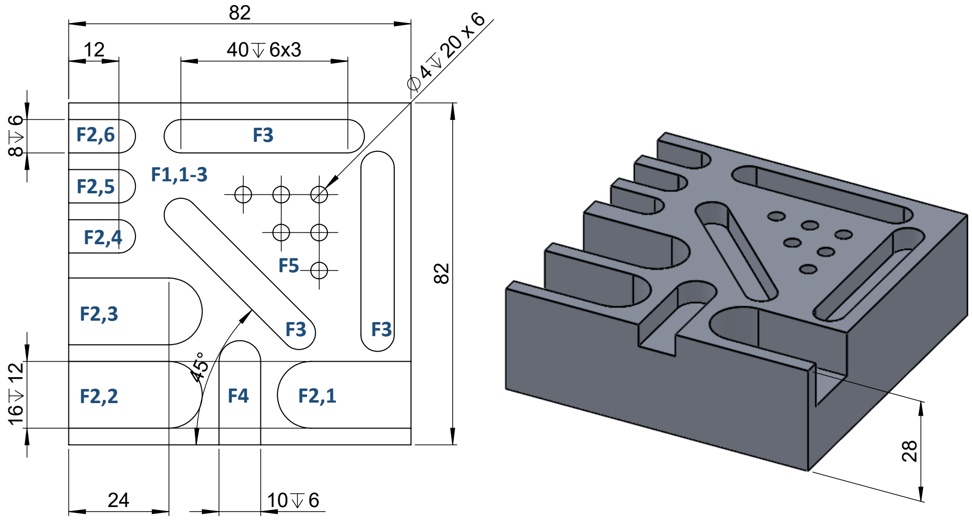

Fig. 3: Reference test part used for developing the adjusted UPLCI model [17]. Please note that features on this part are categorized by operation type (F1–F5). Each category is subdivided further (e.g., F2,1–F2,6) if different process parameters were used to machine that specific feature.

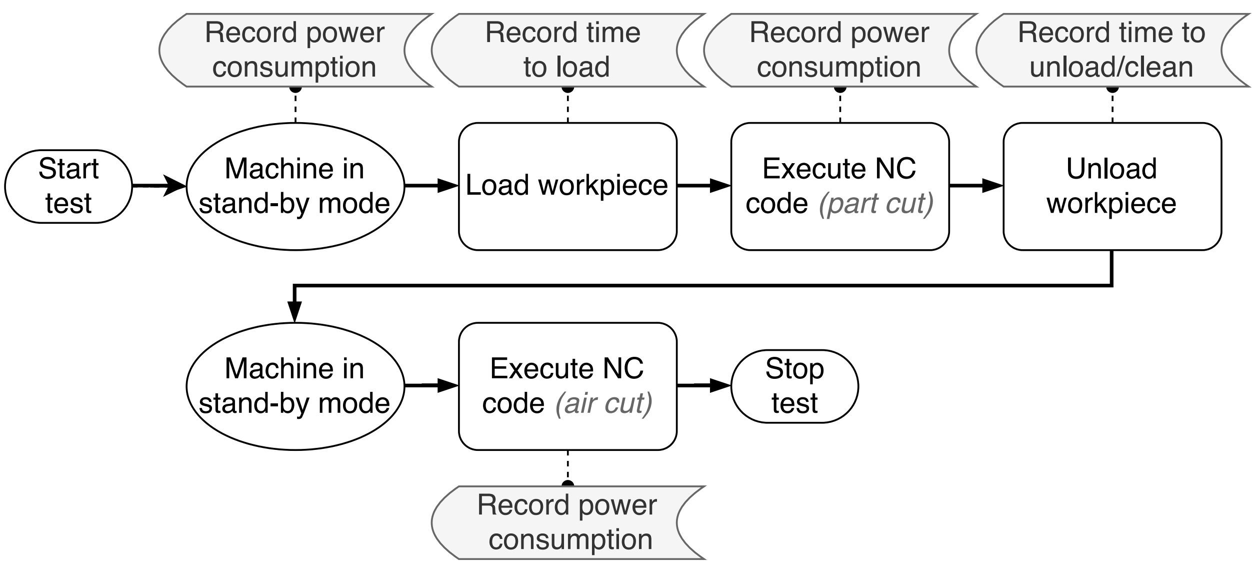

Fig. 4: Procedure for measuring experimental power consumption for the reference test part.

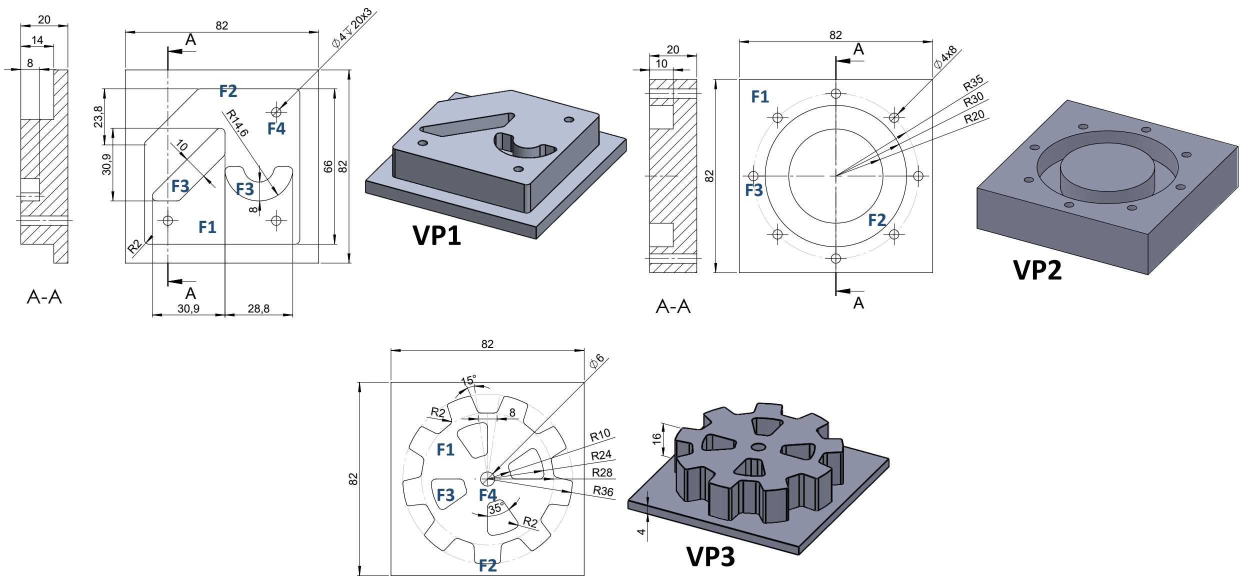

Fig. 5: Validation parts (VP1,VP2, & VP3) used for validating the adjusted UPLCI model. The solid model files for the three parts can be downloaded from https://tinyurl.com/uplci2020.

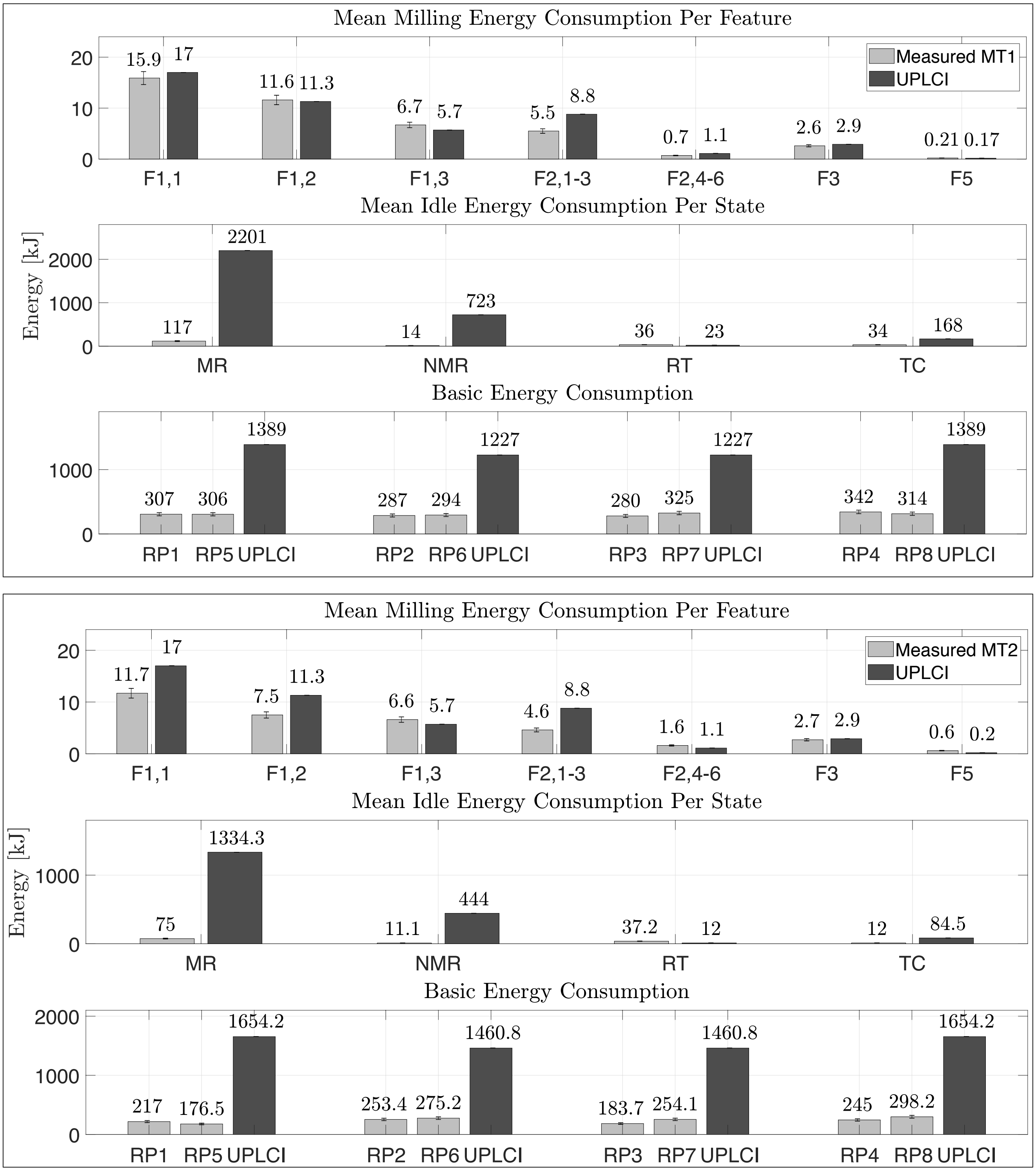

Fig. 6: Comparison of experimentally measured energy consumption on MT1 and MT2 against corresponding estimates from the UPLCI model for the reference test parts. Here, a feature, F#,# represents a specific feature on the reference test part as detailed in Fig. 3. The error bars represent measurement uncertainties in the experiments (±8.5%).

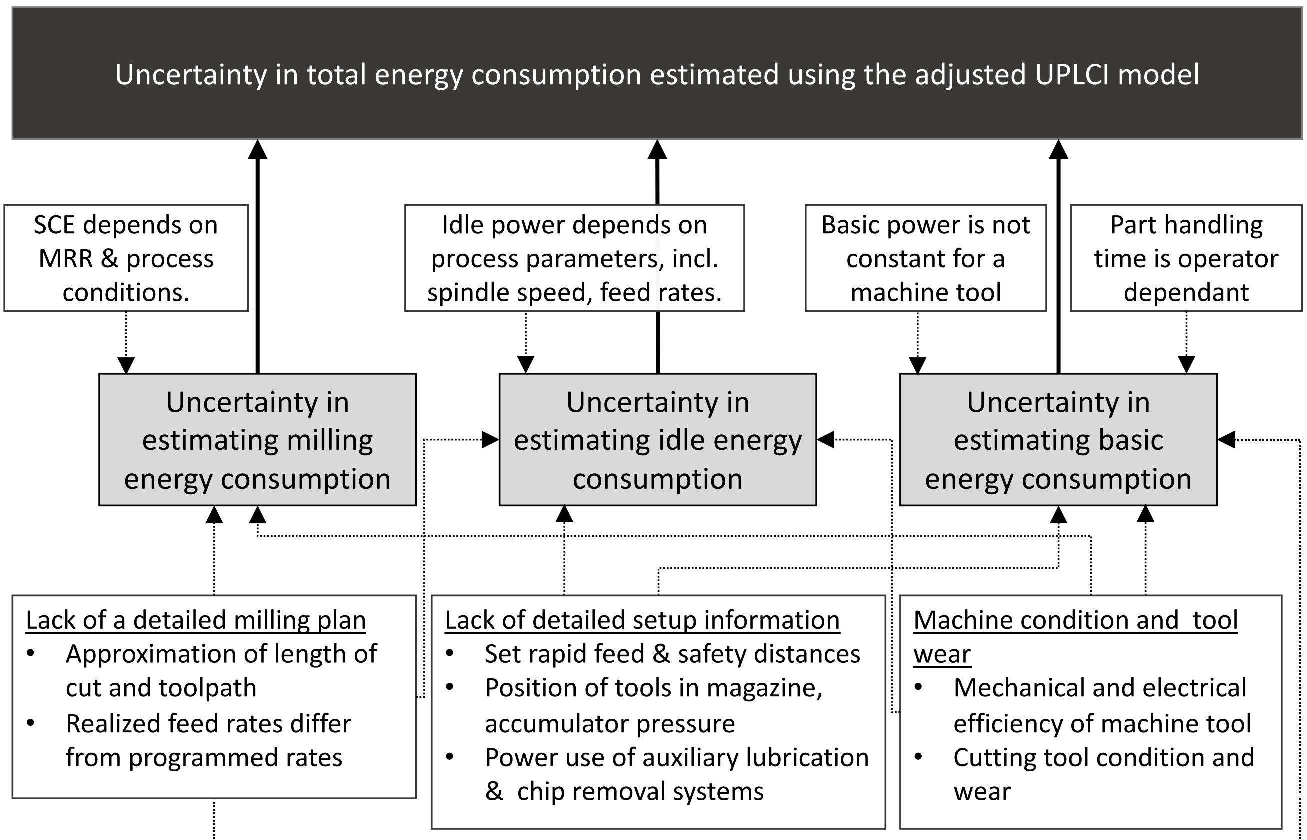

Fig. 7: Factors contributing to uncertainty in the overall energy consumption estimated by the adjusted UPLCI model.

TABLE CAPTIONS

Table 1: Potential sources of uncertainties in the UPLCI model for estimating milling energy consumption.

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Fig. 7: Factors contributing to uncertainty in the overall energy consumption estimated by the adjusted UPLCI model.

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APPENDIX

Assumptions used for estimating milling, idle, and basic energy consumption using the UPLCI milling model. The same assumptions were used for all reference test parts and validation parts.

- SCE for Aluminum 6082 = 0.7 J/s*mm3.
- $t^{uplci}_{load/unload}$ = 19.6 seconds.

The above assumptions were based on empirical estimates detailed in Kalla et al. [8]. Assumptions made with regards to the the two machine tools (MT1 & MT2) are shown in Tbl. 6

Table 6: Assumptions made in the UPLCI milling model to estimate idle and basic power.

Mode	The power consumption is estimated as:	Chevalier QP2040-L (MT1)	Leadwell MCV-OP (MT2)
Idle power (P^{uplci}_{idle})	$\frac{1}{3}$ of the maximum power consumption of the spindle motor	3332.1 W	2797.5 W
	$\frac{1}{2}$ of the maximum power consumption of the feed drives	5595.0 W	1656.1 W
	Rated power consumption of the coolant pump	746.0 W	400.0 W
		9673.1 W	4853.6 W
Basic power (P^{uplci}_{basic})	Assumed as 25% of the maximum power consumption of the machine tool. The UPLCI methodology overestimated basic energy consumption for MT1 & MT2 in the suggested range of 12.5% – 25% of the maximum power consumption. The upper bound of this range was chosen to verify the performance of the adjusted UPLCI model in the worst-case scenario with the greatest estimation error. Please also note the UPLCI methodology offers no guidance on selecting a specific percentage within this range.	3750.0 W	3750.0 W

Table 7: Process parameters for milling the reference part on the two machine tools.

			Chevalier QP2040-L (MT1)				Leadwell MCV-OP (MT2)			
Operation			Spindle speed [rpm]		Feed rate [mm/min]		Spindle speed [rpm]		Feed rate [mm/min]	
o	Name	DoC (h)	Low	High	Low	High	Low	High	Low	High
1,1	Face milling	3	2200	2420	1000	1210	1980	2200	810	1000
1,2		2	2200	2420	1000	1210	1980	2200	810	1000
1,3		1	2200	2420	1000	1210	1980	2200	810	1000
2,1	Groove	12	3500	3850	600	726	3150	3500	486	600
2,2		12	3500	3850	750	908	3150	3500	608	750
2,3		12	3500	3850	900	1089	3150	3500	729	900
2,4		6	5000	5500	300	363	4500	5000	243	300
2,5		6	5000	5500	400	484	4500	5000	324	400
2,6		6	5000	5500	500	605	4500	5000	405	500
3,1	Pocket	6	5000	5500	300	363	4500	5000	243	300
3,2		6	5000	5500	300	363	4500	5000	243	300
3,3		6	5000	5500	300	363	4500	5000	243	300
4	Tro. groove	6	4000	4400	500	550	-	-	-	-
5,1	Drilling	20	2500	2750	150	182	2250	2500	122	150
5,2		20	2500	2750	200	242	2250	2500	162	200
5,3		20	2500	2750	250	303	2250	2500	203	250
5,4		20	2500	2750	300	363	2250	2500	243	300
5,5		20	2500	2750	350	424	2250	2500	284	350
5,6		20	2500	2750	400	484	2250	2500	324	400

Table 8: Process parameters for milling the three validations parts on both MT1 & MT2.

	VP1			**VP2**			**VP3**		
Operation Name	Spindle speed [RPM]	Feed rate [mm/min]	DoC (h) [mm]	Spindle speed [RPM]	Feed rate [mm/min]	DoC (h) [mm]	Spindle speed [RPM]	Feed rate [mm/min]	DoC (h) [mm]
Face milling	2420	1000	3	2420	1000	3	2420	1000	3
Groove	4500	800	16	-	-	-	4500	800	10
Pocket	5000	500	8	4500	800	10	5000	500	10
Drilling	2200	300	20	2200	300	20	2200	300	20

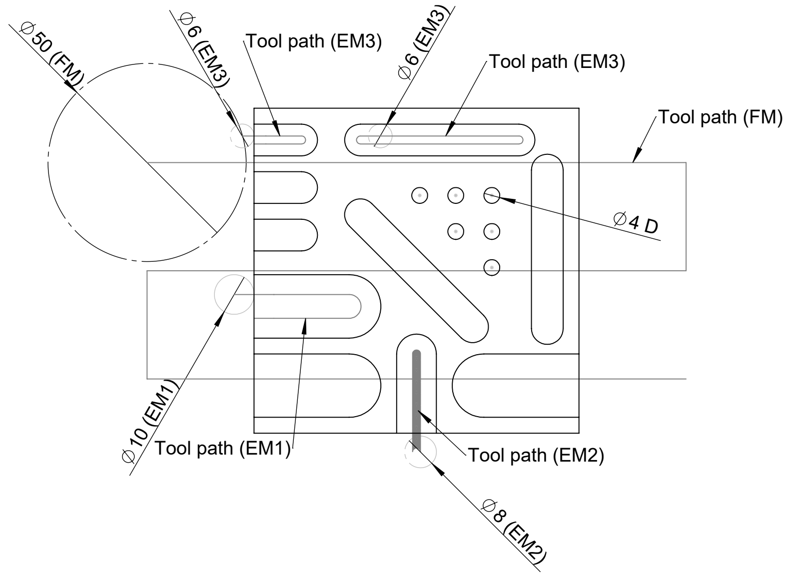

Fig. 8: Milling routing for all reference test parts (RP1,2...,8). Based on this routing plan and the number of layers for each operation (see Appendix Tbl. 7), the total length of cut is estimated to be 2540 mm.

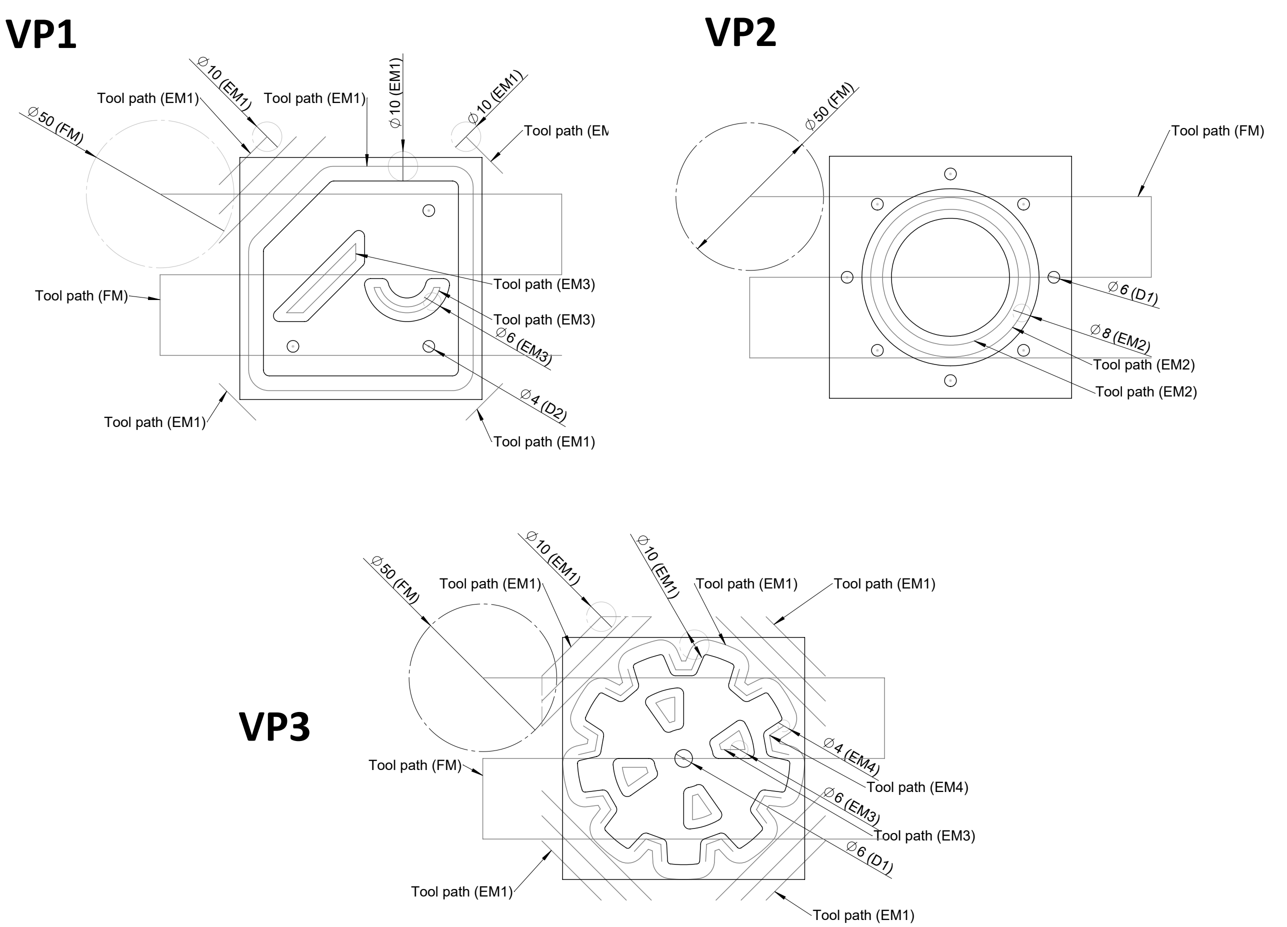

Fig. 9: Milling routing for VP1, VP3, and VP3. Based on these routing plans and the number of layers for each operation (see Appendix Tbl. 7), the total length of cut for VP1, VP3, and VP3 was estimated as 1200 mm, 1052 mm, and 2312 mm respectively.

TABLE CAPTIONS: APPENDIX

Table 6: Assumptions made in the UPLCI milling model to estimate idle and basic power.

Table 7: Process parameters for milling the reference part on the two machine tools.

Table 8: Process parameters for milling the three validations parts on both MT1 & MT2.

FIGURE CAPTIONS: APPENDIX

Fig. 8: Milling routing for all reference test parts (RP1,2...,8). Based on this routing plan and the number of layers for each operation (see Appendix Tbl. 7), the total length of cut is estimated to be 2540 mm.

Fig. 9: Milling routing for VP1, VP3, and VP3. Based on these routing plans and the number of layers for each operation (see Appendix Tbl. 7), the total length of cut for VP1, VP3, and VP3 was estimated as 1200 mm, 1052 mm, and 2312 mm respectively.