Journal of Machine Engineering, Vol. 15, No.2, 2015

downtime cost, machine tools,
predictive calibration,
accuracy

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DERIVATION OF A COST MODEL TO AID MANAGEMENT OF CNC MACHINE TOOL ACCURACY MAINTENANCE

Manufacturing industries strive to produce improved component accuracy while not reducing machine tool availability or production throughput. The accuracy of CNC production machines is one of the critical factors in determining the quality of these components. Maintaining the capability of the machine to produce in-tolerance parts can be approached in one of two ways: run to failure or periodic calibration and monitoring. The problem is analogous to general machine tool maintenance, but with the clear distinction that the failure mode of general machine tool components results in a loss of production, whereas that of accuracy allows parts to be produced, which are only later detected as non-conforming as part of the quality control processes. This distinction creates problems of cost-justification, since at this point in the manufacturing chain, any responsibility of the machine is not directly evident. Studies in the field of maintenance have resulted in cost calculations for the downtime associated with machine failure. This paper addresses the analogous, unanswered problem of maintaining the accuracy of CNC machine tools. A mathematical cost function is derived that can form the basis of a strategy for either running until non-conforming parts are detected or scheduling predictive CNC machine tool calibrations. This is sufficiently generic that it can consider that this decision will be based upon different scales of production, different values of components etc. Therefore, the model is broken down to a level where these variables for the different inputs can be tailored to the individual manufacturer.

1. INTRODUCTION

Manufacturing companies across the globe are increasingly concerned about their ability to innovate and compete in the fast-changing technology world. Complex and high-value manufacturing often requires a high level of accuracy; the demands of consumers and end-users are for lower cost, more efficient and resource-lean products. CNC machine tools used for production are required to operate within accepted limits of tolerance, which become ever tighter with the availability of new enabling technology and greater customer drive. Notwithstanding this ambition for higher accuracy, increased availability of production machines is a fundamental requirement to maintain competitiveness. These two goals can be perceived as having conflicting requirements; time to maintain accuracy

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can be at the expense of time for producing parts. However, the push for increased availability must take into account the need that this “availability” is to produce parts within tolerance, not non-conforming parts. Therefore, a suitable strategy is needed to maintain accuracy without imposing too onerous a regime in terms of lost production during measurement.

Machine tool “failures” in industrial organisations interrupt production operations and cause production loss, which has a direct cost-to-business and potentially a significant detrimental impact to future production. These failures of mechanical or electrical elements are often “binary”, where the machine either works or is unable to produce. Here, the need for repair is clear. However, the failure mode for accuracy is somewhat more complex.

No part is ever made perfectly and no measurement is exactly correct. Therefore, achieving tolerances on manufactured components is only assured if the sum of all sources of inaccuracies does not exceed the total tolerance. This in itself contributes to the discussion of machine accuracy, since it represents only one component of the total error budget and solutions are often found by making compensating adjustments in other areas. For example, by compensating with small offsets to the CNC program or work-piece offsets, modifications to part alignment or fixtures, etc. Herein lies the main argument against regular maintenance of the machine to preserve accuracy; a machine can continue to produce parts by adapting the process to suit changing conditions.

There is therefore often a resistance to spend time understanding the error budget at a granular level if the overall statistical process control (SPC) results show good consistency. There are a number of ways in which the machine can remain reliably capable:

- using a machine with significantly better accuracy than required to meet component tolerance, although this requires a higher capital investment
- making frequent, minor corrective actions, although this can reduce traceability and can introduce unwanted variability
- predictive maintenance, focusing on the accuracy aspects of the machine, although this can impact on machine availability

In fact, application of each of these strategies can be justified for different circumstances. This paper does not seek to provide a universal answer to the question of “the best” strategy, but rather provides the derivation of a mathematical tool that can be applied to a wide sample of machining processes to understand better the cost of maintaining machine accuracy, but also the implications of non-conformance.

Predictive maintenance for accuracy, or predictive calibration (PdC), is one possible way of ensuring the machine is capable of achieving tolerances and can form part of a continuous improvement process in maintenance [11]. This would allow scheduling of time to carry out measurement tasks to ensure that accuracy levels were maintained. The converse is true; where high production rates are demanded, then this can affect the ability to meet PdC requirements. The problem is exacerbated where two independent departments have “ownership” of the conflicting Key Performance Indices (KPIs); the maintenance department is required to ensure accuracy, while the production department is measured against production rate. This is why a company-wide understanding and approach is vital [16].

Maintenance programs such as Total Productive Maintenance (TPM), recommend what is called 'autonomous maintenance', which aims to increase the skill levels of maintenance personnel so they can better understand, manage and improve their machines and the production process. The objective is to change workers from being reactive to proactive, to achieve optimal conditions that eliminate stops as well as reducing the production of non-conformance parts, rejects and machine failures [16]. Predictive maintenance (PdM) is one approach that has been successfully applied to mitigate the effects of unexpected failure by scheduling controlled production stoppages [20], rather than reacting to a breakdown. Predictive maintenance is a tool that has been adopted in some industries to improve operational efficiency and reduce maintenance cost [3]. As a result, monitoring equipment that provides information about the condition of manufacturing systems has evolved rapidly over recent years.

Calibration is a fundamentally accepted process required to maintain the quality of measuring machines [14]. It can also be applied to the production process to help control output quality and maintain the credibility of the machine tool for measurement, such as in-process probing [2]. Full machine tool calibration requires measurement of a number of error sources; there are 21 sources of error for a 3-axis machine tool, with many more on complex machines, typically taking up to one week of measurement time on large machines. The reason for repeatedly calibrating an instrument, machine tool or any other machine is that their performance can drift over time and usage in both their mechanical and electrical response. When considering machine tool accuracy, bedding in, wear of components and collision are some reasons for this change. The prescribed interval between calibrations tends to be subjective; a fixed "annual" calibration is sometimes adopted as part of a quality paper-trail, but more likely calibration is undertaken as a reaction to change in the consistency of the machine's output. Building a database of inspection history by measuring the machine on a regular basis, ideally with relatively non-invasive methods, would make the decision of scheduling the more extensive calibration a better-informed process.

Successful measurement depends on accurate metrology systems (equipment and software) that are traceable to international standards, an understanding and minimisation of measurement uncertainty assisted by application of good measurement practice. Schwenke and Knapp [15] stated that when reporting the error parameters of a machine, an uncertainty must be connected to the reported numbers. Thus the usefulness of the measurements can be determined; parameters can be compared to their specifications, taking the measurement uncertainty into account. Uncertainty is defined as a "non-negative parameter characterising the dispersion of the quantity values being attributed to a measurand, based on the information used" [1]. The effect of uncertainty can have a significant impact on production quality control.

Fig. **1** 1 illustrates the conformity and non-conformity zones based on the uncertainty value and the lower and upper specifications limit. The remainder is uncertain. From this illustration only measurement values that fall within the conformance zone are certain, within the given confidence level, to be within the tolerance. Minimising the uncertainty of measurement can increase the conformance zone, reducing false acceptance and rejection [12].

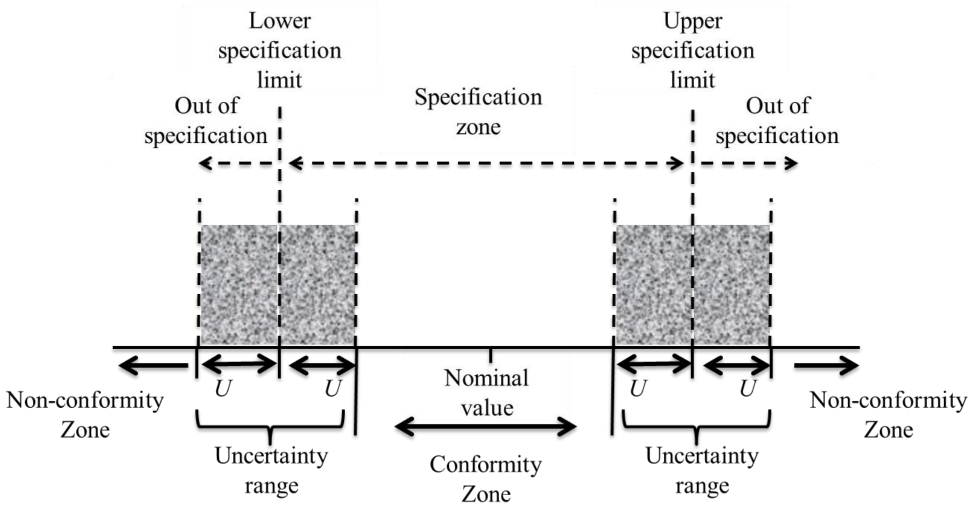

Fig. 1. The effect of measurement uncertainty on reducing the specified tolerance band when examining conformity, *U* is the measurement uncertainty [1]

However, this is where potential conflict can arise; minimising downtime might increase uncertainty, which is to say reduce data quality. Manufacturing industries need their production machine tools to be measured quickly. However, quick checks can cause inaccuracy if they are not well performed. Measurements should be reliable in identifying the dimensions of concern to the degree of accuracy required and should be sufficiently robust to eliminate false positives. Measurements should be conducted in accordance with standard procedures. These could be according to international (ISO), national, company or original equipment manufacturer (OEM) standards to allow the ease of traceability of the test method. This will enable test reproducibility for different users and improve efficiency [19].

As discussed, PdC can be used as part of a hybrid maintenance strategy. However, the negative factors are the cost of the metrology equipment needed and the necessary skilled labour and training costs required to use them effectively. Additionally, such measurements can only be taken when the machine is not producing parts, thus the opportunity cost must be considered. Establishing an optimised PdC strategy is a non-trivial task that must be rolled out as a controlled process programme, taking into account the available technology and their relative merits. Table 1 provides brief comparison between different calibration and measurement approaches.

Since many preventative (inspection, calibration) tasks for maintaining the accuracy of CNC machine tools require them to be removed from production, the evaluation of downtime cost has become a key issue in optimising the frequency of calibration and maintenance actions [22].

The "downtime" of the machine is an important part of the cost calculation. In the product manufacturing cycle, several engineering tasks like machining design, process planning and machine maintenance/calibration scheduling have to be performed. The implementation of these tasks, in particular calibration actions, mainly involves information processing and decision-making. If this can be performed in parallel to part production then the cost has less impact than if it is sequential and requires the machine to stop outputting parts. Therefore, downtime for calibration is often seen as a non-value-added cost.

Table 1. Comparison between calibration approaches [17]

Aspect	Quick check tests	Full calibration	On-machine artefact probing	Post-process measurement
Typical Duration	30 minutes [21]	2 to 5 days [9]	5 to 10 minutes	A few hours
Target	Measure and monitor	Measure and compensate	Check, analyse and rework to increase part quality	Inspect the work piece
Environment	Workshop environment	Workshop environment	Workshop environment	Controlled environment
Data suitable for comparison	Statistics and process control	Statistics and process control. More skilled interpretation	Statistics and process control	Statistics and process control
Process	Occurs while the machine is running but machining process interrupted	Occurs while the machine is out of production	Performed as part of machining procedures	Occurs after machining and off the machine
Access	Operator	Skilled	Operator	Skilled
Risk of missing important data	High risk due to low coverage	Low risk due to high coverage	Low to Medium risk depending upon relevance of artefact to part	Low risk

Machine downtime can be understood as the time when the machine is not producing saleable parts. However, Yam defined downtime as: “The amount of time a machine or system is not functioning due to stoppages in a given shift or time period”. He stated that downtime should not include idle time or time the machine or system is waiting for inputs. Therefore downtime depends on stoppages and company policies [24]. Whether planned or unplanned, such lost production is intuitively costly to manufacturing organisations [6]. It is essential to estimate downtime costs in order to support manufacturing decision-making. Crumrine and Post [5] stated that factories could lose from 5% up to 20% of their productive capacity because of downtime. They also estimate that 80% of industrial facilities are unable to estimate their downtime accurately, and suggested that many facilities underestimate their total downtime costs by as much as 200-300%. The great majority of machine tool unavailability is the result of planned downtime that occurs due to required maintenance. “Although unplanned downtime may account for 10% of all downtime, its unexpected nature means that any single downtime incident may be more damaging to the industry, physically and financially, than many occurrences of planned downtime" [4]. To put this into a financial context, typical hourly rates for machine tools are estimated between €90 and €175 per hour. Justification is needed if this time is spent in calibration rather than production.

Jantunen and Baglee [7] stated that; "Very little is known or published about the importance and the role of various failure models in different industrial sectors. Thus, if failure models are not understood and handled properly, the use of condition-based maintenance cannot lead to financial benefits". Existing studies in the field of predictive maintenance have resulted in cost calculations for the downtime associated with machine failure [13]. However, there is a lack of the availability of a global model that could be used for any machine tool scenario. It could be said that although PdC and PdM are different applications, they can follow the same downtime cost calculation process to decide their applicability for a given asset. The surveyed literature was commonly found to be focused on specific industries and conditions and only investigated downtime costs associated with production loss and ignored other possible added costs due to downtime [18].

This paper presents a derivation of a cost model to aid management of machine tool accuracy maintenance, with variable inputs depending upon the levels of production and product value, cost of labour inputs and downtime required for calibration actions.

2. COST MODEL APPROACH

The proposed methodology is to consider the machine tool accuracy problem and error measurement related costs from installation. This algorithm is intended to lead to a calculator that could predict the benefits of different maintenance regimes based upon different factors such as volume and value of manufacturing. This algorithm can be used as part of an optimising technique to determine the most appropriate of these calibration approaches, adoption of which could also increase the mean time to failures (MTTF) of machines. This work will ultimately lead to a technical-driven management tool that can optimise the frequency of calibration to reduce unnecessary downtime while maintaining the machine at the required tolerance. It is worth stating explicitly that the optimal number of PdC actions can be zero in some cases; there are scenarios where PdC is not the most suitable approach.

The emphasis in this section will be on the identification of the elements of direct and indirect costs related to the machine tool accuracy problem. Since the majority of practical models in maintenance field are based on ambiguous data e.g. (subjective data, expert opinions), it is important to expose in the model cost factors that could otherwise be overlooked, or be otherwise form part of a "lumped" model. Reasonable assumptions of those factors that have an indirect contribution to the downtime cost should not cause major problems [23].

Total costs of machine tool downtime are composed of several different cost elements. Breaking down the factors that contribute to determining the downtime cost is necessary to cover a broad range of machine tool assets, production types and scales. Downtime costs must be calculated per event. Thus; calculate/record the time from the first occurrence of machine tool breakdown to the time when machine tool was back into full production. The first step in the cost estimation is to make a process map for the downtime related sources of costs. This is shown in Table 2 .

Table 2. Machine tool accuracy related source of costs

Source of cost	**Explanation**
Measurement/ Benchmarking	
Cost of measurement equipment (metrology)	Direct or indirect where you metrology need to be hired. If it is direct, a cost of training and calibrating the measurement equipment may need to be added.
Measurement labour	Internal or external labour. This includes the cost of machine operator to drive the machine around. Contractor induction may be included under this cost.
Lost production	Cost of lost production during measuring the machine.
Utilities and tools	Temporary utilities and tools including energy and cooling.
Start-up of production	
Warm-up cycle	The cost due to resetting and warm up period. This includes offset adjustment, program selection and replacement of fixtures.
Cost of pass-off part	This is assumed to be a single process. This includes: Raw material, cutting tool, energy, coolant, air compressor, energy, and machining cost.
Cost of non-conformance	
Scrap	This includes lost production, raw material, and cost of production processes. Recycling of the scrap material might be an income if it could be sold or a loss if it cannot be sold.
Rework	Includes the inspection, investigation, quality control extra hours due to rework and lost production during rework.
Late penalties	Penalties, fines and shipping costs due to non-conformance parts.
Cost of reaction	
Cost of reaction	This could include: Additional quality control tests, measurements, management involvement, lost confidence implies possible additional quality control, and reduce throughput.
Low accuracy inefficiency	
Cost of low accuracy inefficiency	This includes: Increased tool wear, reduced efficiency (feed rate), and cost of shift change to overcome problems. This will increase the risk of non-conformance.
Cost of waiting to react	Lost production
Time for quality control to detect non-conformance	This includes the time to: Travel to quality control, temperature stabilisation of the part, time to measure on CMM, and time to report back to production manager.

Typical part manufacturing planning is summarised in Fig. 2, which shows that it is divided into two stages. The first stage is the part design, where the study and preparation for the desired design criteria takes place. This is followed by the part manufacturing process, where the material is procured, rough-machined, finish-machined and inspected.

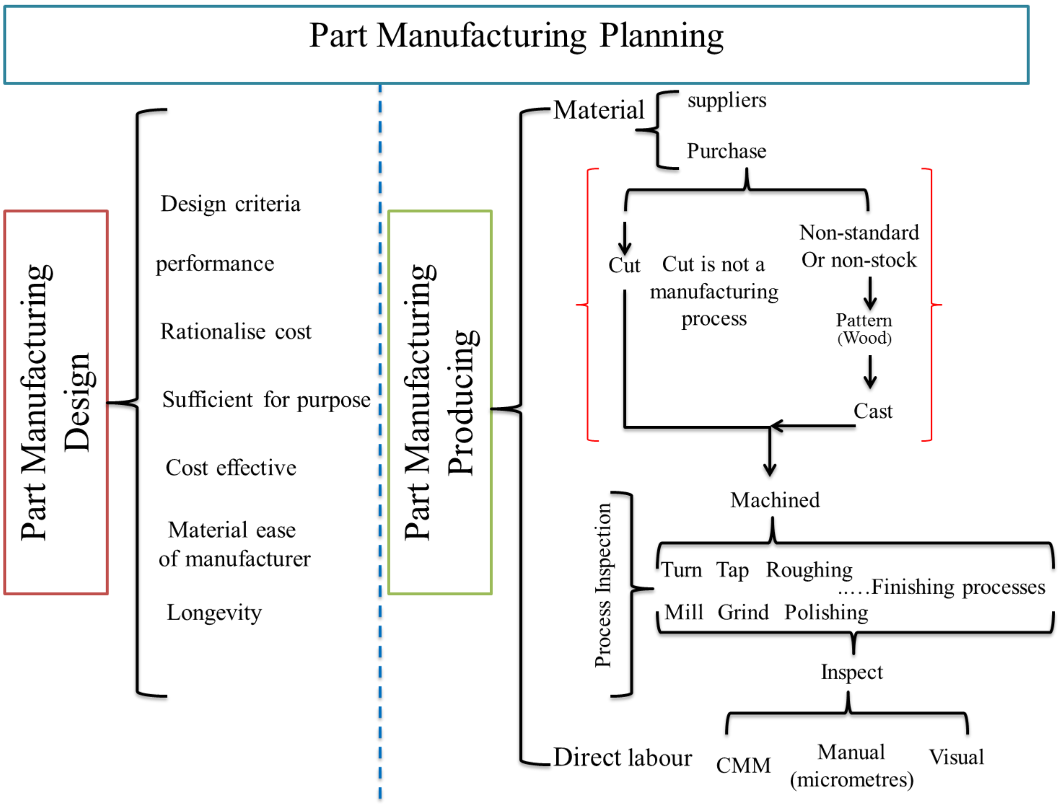

Fig. 2. Part Manufacturing Planning

3. COST MODEL DERIVATION

The following naming convention is used throughout:

CV_A	Cost value of A
CR_B	Cost rate of B; € per hour.
QV_C	Quantity value C; a numeric, unitless value
T_D	Time period D (hours)
$t_{(i)}$	An instant in time
QC_{PPI}	Quality control post process inspection
QC_{IPI}	Quality control In-process inspection
$QC_{MC\ error\ mapping}$	Quality control Machine error mapping
$QC_{MC\ verification}$	Quality control Machine verification

First, assume a machine tool run-to-fail scenario for the cost function derivation. There are no predictive calibration actions and detection of failure only occurs during post-process inspection (PPI) in the quality control department. Fig. **3**3 shows machine tool run-to-failure scenario and its related costs. There is a period between t_1 and t_3, between PPIs, where there is no feedback on the quality of the product. In this scenario, if the machine goes out of tolerance at time t_2 it could be assumed that the parts between t_1 and t_2 have been produced accurately but those produced between t_2 and t_3 have not. However, lack of feedback means that the value of t_2 is unknown to the production managers; it could be anywhere between the two PPIs. There is a further amount of time between the PPI action *n* and t_3, which is the time at which the production is halted due to non-conforming parts detected. This time period could vary from minutes to days depending upon the responsiveness of the production department to detection of non-conformance. There will also be a period of time for investigation, $T_{investigation}$, including delay while the calibration action is scheduled, measurement and while remedial action is taken. Production will be interrupted while the machine is calibrated, then it will start again at time t_4.

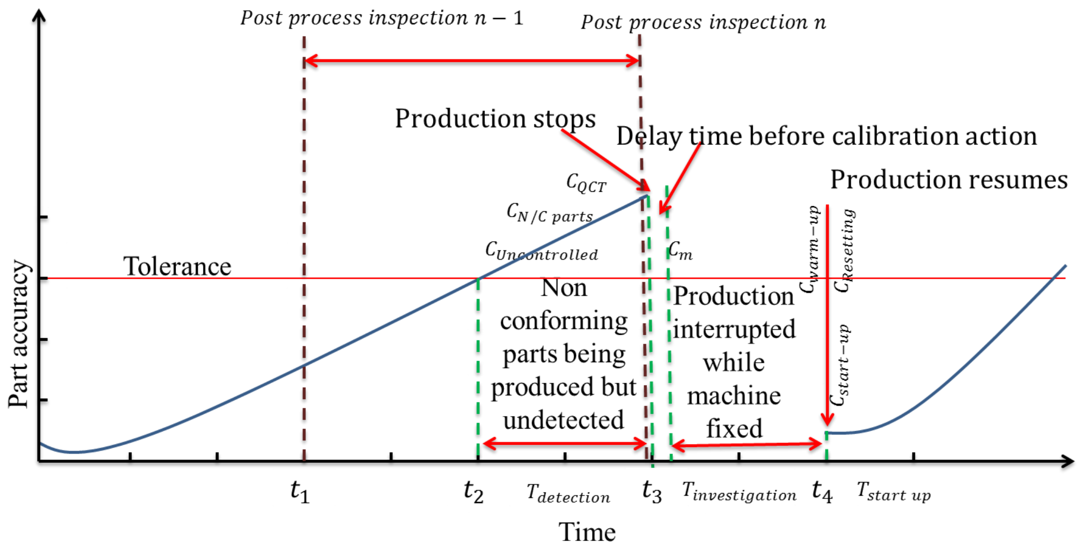

Fig. 3. Machine tool; run to fail scenario and the related costs

3.1. COST PER PART

The value of the part (product), and therefore the cost of materials, is an important component of the cost model. Material costs can be divided into direct and indirect costs. The latter are those costs that are not directly added into the product. For example: coolant oil, lubricants for machines, nuts, bolts and screws. Direct costs are more significant for the calculation because they are directly input to the product; the cost of raw materials for a particular product is the main contributor. It is a function of the amount of input (raw) material and its unit cost. The cost value of the part is represented in more detail in equation (1).

$$CV_{part} = CR_{manufacturing} * T_{cycle} + CV_{total\ input\ components} \tag{1}$$

Where:
CV_{part} is the value of the part at the end of the manufacturing cycle;
$CR_{manufacturing}$ is the cost rate of part production in parts € per hour (equation (2));
T_{cycle} is the cycle time in hours to produce one part and;
$CV_{total\ input\ components}$ is the total value of the raw materials per part (equation (9)).

Factory burden, also referred to as manufacturing overhead, is an indirect manufacturing-related cost that is incurred when a part is produced. Along with costs such as direct material and direct labour, the cost of manufacturing burden must be assigned to each unit manufactured.

$$CR_{manufacturing} = CR_{total\ machinest\ labour} + CR_{burden} \tag{2}$$

Where:
$CR_{total\ machinest\ labour}$ is the rate of total machinist labour, € per hour (equation (3))
CR_{burden} is the cost rate of indirect manufacturing burden incurred during parts production € per hour (equation (5)).

Direct labour is sometimes considered the most obvious loss during a downtime incident [5]. However, if the part value per hour is high then the main loss can be the machine not producing parts. Direct labour cost is the cost of labour applied to a particular product or using a particular machine. This includes the wages of labourers manufacturing the product. Some labourers are considered to remain idle for the period of downtime, although the case where only partial loss of productivity by the worker is considered in equation (4). Direct labour cost can be calculated by multiplying the direct labour time and wage rate. Training cost to direct labour cost is not presented separately since it could be included in the labour cost itself. Hence, the total labour cost is calculated based upon how much labour is contributed by different personnel. It will be represented as in equation (3) to reflect different workers with different labour rates. The total cost of labour for the machinist could be expressed as:

$$CR_{total\ labour\ machinist} = \sum_{i=1}^{n} QV_{i\ (labour\ machinist)} * CR_{i\ (labour\ machinist)} \tag{3}$$

Where:
$QV_{i\ (labour\ machinist)}$ is the quantity of machinists labour involved in the production process.
$CR_{i\ (labour\ machinist)}$ is the cost rate of machinist, € per hour.

The quantity of labour refers to the number of operators involved (machinists) in the production process. It may or may not be an integer number, depending upon whether multiple tasks are performed in parallel by individual workers. For instance, an operator working on two production machines in parallel would be considered as 0.5 in the number of operators for each machine, although this division could be more accurately reflected depending upon the intensity of labour required on a particular machine. There might be cases where two operators working on the same machine are needed, although this is not common. Under this circumstance, equation (3) would include multiple indices.

$$0 < QV_{i\,(labour\ machinist)} \leq 1 \tag{4}$$

Manufacturing burden includes elements such as electricity and air supply used to operate the manufacturing machine and other equipment, depreciation on the factory equipment and building, and it might include factory personnel (other than direct labour). Factory overhead includes all manufacturing cost besides direct materials and direct labour. It is used directly for production, but it fails to be credited directly to a particular product cost. Most elements of manufacturing overhead do not have direct relationship to processing of the product. In actual production costing, if the workshop produces only one product then the manufacturing costs can be reckoned directly in the production cost of the product. Otherwise, the manufacturing cost is reckoned in various products by using a reasonable allocation method [10]. The cost rate of burden CR_{burden} is defined as being already calculated for the length of time. For overall burden, it is simplified as a total 12 months divided by a rate per hour time. The machine charge would have to cover all the costs. In order to do this, the number of hours per year that the machine will be producing parts must be calculated and divide this figure into these costs. This will give a machine rate per hour.

$$\begin{aligned} CR_{burden} = \big(&CR_{energy} + CR_{coolant} + CR_{air\ comp\ energy} + CR_{lubricant} \\ &+ CR_{sundries} + CR_{Machine\ depreciation} + CR_{others}\big) \end{aligned} \tag{5}$$

Where:

CR_{energy} is the cost rate of energy consumed during part production, € per hour.

The rest are the cost rate of coolant, air compressor, lubricant, and sundries (other) used during part production per manufacturing hour.

CR_{burden} is different during production and non-production. For example, when the machine is running the air compressor will be active and have running costs. If the machine is completely stopped during a downtime period then the cost will not be incurred. Another example is the potentially lower cost when the machine is being measured; the axes are moving, but the effect of cutting force, rapid acceleration, etc. will be much less onerous. For simplification, this will be dealt with separately in the assumptions made in the variables for the case studies in future work.

To simplify the equation in this paper, only the energy element (CR_{energy}) of the cost rate of burden CR_{burden} will be varied CR_{energy} and the others remain constant for simplification. Therefore, the cost rate of burden equation that will be used in this paper will be simplified to:

$$CR_{burden} = \big(CR_{energy} + CR_{others}\big) \tag{6}$$

There will be cases where the machine is not in production. For example, scheduled or unscheduled maintenance or stoppage due to detected non-conforming parts. Equation (8) gives the cost value of non-production $CV_{machine\ non-production}$ for the whole period where the machine is not producing parts. It is naturally a function of the rate of costs (equation (7)) and duration of stoppage.

$$CR_{machine\ non-production} = CR_{burden} + CR_{idle\ labourer} \tag{7}$$

Where:

$CR_{machine\ non-production}$ is the cost rate of machine non-production in € per hour due to work stoppage due to any cause.

$CR_{idle\ labourer}$ is the cost rate per hour of idle labourer waiting for the machine to resume production, € per hour.

$T_{non-production}$n is machine idle time, or waiting time.

$$CV_{machine\ non-production} = CR_{machine\ non-production} * T_{non-production} \tag{8}$$

The cost of input components to the manufacturing process can be presented as:

$$CV_{total\ input\ components} = \sum_{i=1}^{n} QV_{i(input\ components)} * CV_{i\ (input\ components)} \tag{9}$$

Example1: A machine tool pallet that takes three input components at a time to produce one finished part (Fig. 4). These components are perhaps of different material or simply have different values due to the number of pre-machining processes.

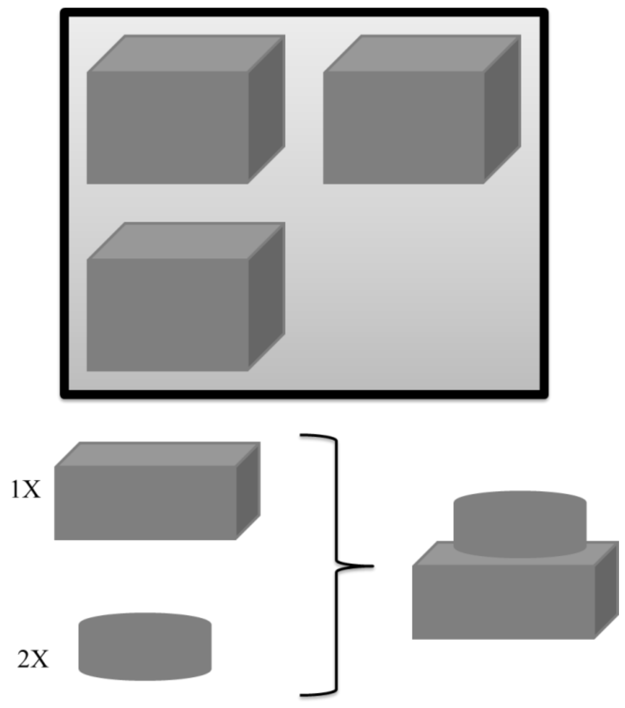

Fig. 4. Example of a machine tool pallet that takes three different input components

Substituting equation (2) and (9) into equation (1) gives the value of the part at the end of the manufacturing cycle:

$$CV_{part} = \left(\sum_{i=1}^{n} QV_{i\,(labour\,machinist)} * CR_{i\,(labour\,machinist)} + CR_{burden}\right) * T_{cycle} + \sum_{i=1}^{n} QV_{i(input\,components)} * CV_{i\,(input\,components)} \tag{10}$$

3.2. COST OF UNCONTROLLED PERIOD

Cost of uncontrolled production has a direct relationship with the time spent to detect that the machine is producing non-conforming parts due to the machine going out of accepted performing tolerance. The cost of a scrapped part is directly affected by variable manufacturing parameters such as energy costs, raw material costs, time to manufacture, etc. For this reason, the equation produced in this study must be considered a “live” tool which must be reanalysed as these cost variables change.

$$CV_{Uncontrolled} = CV_{scrap\,units\,uncontrolled} + CV_{rework\,units\,uncontrolled} \tag{11}$$

Where:

$CV_{scrap\,units\,uncontrolled}$ is the cost value of scrapped units produced during the uncontrolled period of production.

$CV_{rework\,units\,uncontrolled}$ is the cost value of reworked parts produced during the uncontrolled time of production.

$QV_{uncontrolled\,parts\,manufactured}$ is the quantity of units manufactured during the uncontrolled time of production (equation (12)).

$T_{detection}$ is the time at which faulty parts are detected (equation (12)).

T_{cycle} is the part manufacturing time (equation (12)).

Define:

$$QV_{uncontrolled\,parts\,manufactured} = \frac{T_{detection}}{T_{cycle}} \tag{12}$$

Then:

$$CV_{scrap\,units\,uncontrolled} = P_{scrap} * QV_{uncontrolled\,parts\,manufactured} * CV_{part} \tag{13}$$

Cost value of rework might be a small percentage of the whole manufacturing process for the part. However, this will be decided by the length of the time of the rework process.

$$CV_{rework\ units\ uncontrolled} = P_{rework} * QV_{uncontrolled\ parts\ manufactured} * CR_{manufacturing} * T_{rework} \tag{14}$$

Substituting equation (13) and equation (14) into equation (11) gives:

$$CV_{Uncontrolled} = P_{scrap} * QV_{uncontrolled\ parts\ manufactured} * CV_{part} + P_{rework} * QV_{uncontrolled\ parts\ manufactured} * CR_{manufacturing} * T_{rework} \tag{15}$$

Where $P_{scrap}$and $P_{rewo1rk}$ are the probabilities of a scrap or part needing rework respectively.

$P_{conforming}$ is the probability that the part conforms despite the nominal machine tolerance is being exceeded.

$$P_{scrap} + P_{rework} + P_{conforming} = 1 \tag{16}$$

Example2: Assuming twelve hours of uncontrolled time before the machine out-of-tolerance fault is detected, $T_{detection}$, and that the machine takes two hours to make a part, then:

$QV_{uncontrolled\ parts\ manufactured} = \frac{12}{2}$ = 6 uncontrolled parts manufactured.

Example3: A production of possible 100 parts during a manufacturing cycle T_{cycle} with probabilities of:

$$P_{scrap} = 10\% ------------------- number\ of\ scrap\ items = 10$$
$$P_{rework} = 70\% ------------------ number\ of\ rework\ items = 70$$
$$P_{conforming} = 20\% ------------- number\ of\ conforming\ items = 20$$

In the remainder of this discussion, the machine tolerance will be assumed to be exact; if the machine is out of tolerance then it is guaranteed that parts will be produced out of tolerance). In this case, $P_{conforming} = 0$

3.3. COST OF EXTERNAL IMPACT OF PRODUCING NONCONFORMING PARTS

The cost due to producing non-conforming parts may include losing contracts due to reputational harm because of customer dissatisfaction [17]. It may also include the cost of shipping, fines and penalties, delayed orders, or delivery of poor quality goods or services. A non-conforming part produced needs either additional part rework to maintain customer satisfaction or major activities will be required to rectify the situation for the customer.

In this work the impact cost value of non-conforming parts "customer impact" is the additional cost due to shipping uncontrolled parts. This is then split into the case where faulty parts are detected upon receipt by the customer and the case where the faulty part is then used by the customer with consequential damage.

$$\begin{aligned} CV_{nonconforming\ parts\ customer\ impact} &= \left(CV_{Shipping} + CV_{fines} + CV_{penalties}\right) \\ &* \left(QV_{uncontrolled\ parts\ manufactured} * \left(1 - P_{conforming}\right)\right) \end{aligned} \tag{17}$$

Where:

$CV_{nonconforming\ parts\ customer\ impact}$ is the cost due to producing non-conforming parts.

$CV_{Shipping}$, CV_{fines} , $CV_{penalties}$ are the cost value of the additional cost due to shipping uncontrolled parts.

This is a simplification, as in some cases penalties will be on a time basis rather than a number of parts basis. Moreover, the problem of sending faulty parts is a big concern related to how much quality control is effective. However, detailed consideration of this aspect is outside the scope of this paper. Nevertheless, the overarching theme of the paper requires consideration be given to the value of consequential costs. If they are high then every part should be checked and the need to have more regular validation of the machine can also be justified. If the overall cost is lower then, this requirement can be relaxed

3.4. QUALITY CONTROL COST

Process control is concerned with monitoring quality while the product or service is being produced. "The costs of quality are essentially the cost of failures or defects and trying to avoid the failure of such as inspection and training" [8]. It is very important to consider quality control time related to quality inspection. This usually involves senior/skilled personnel to interpret data to find fault.

$$CV_{QC\ total} = CV_{QC\ regular} + CV_{QC\ reactive} \tag{18}$$

Where:

$CV_{QC\ total}$ is the total cost value of quality control actions.

$CV_{QC\ regular}$ is the cost value of regular control inspection which might include: CV_{PPI} the cost of any post process control action required, and CV_{IPI} the cost of in process actions taken during part manufacturing process (equation (19)).

$CV_{QC\ MC\ error\ mapping}$ is the cost value of regular machine measurement.

$CV_{QC\ MC\ verification}$ is the cost value of any quality control action needed to double check that the machine is functioning properly even after a regular machine measurement but produced a faulty part.

$CV_{QC\ reactive}$ is the cost value of reactive control actions. It is not going to be simplified any further here and it will be taken a single-value.

And;

$$CV_{QC\ regular} = CV_{QC\ PPI} + CV_{QC\ IPI} + CV_{QC\ MC\ error\ mapping} + CV_{QC\ MC\ verification} \tag{19}$$

Machine error mapping might include both regular (proactive) and irregular (reactive) machine calibration. In the case where a critical (highly utilised) machine breaks, rapid reactive maintenance is likely to be demanded. Such a time-sensitive reaction will probably attract a premium on costs to have the fault remedied and the machine back into production as soon as possible. However, $QC_{M/C\ error\ mapping}$ will be generalised and taken as a single-value in this stage of the work.

The terms required for equation (18) and equation (19) are provided below:

$$CV_{QC\ PPI} = T_{totalPPI} * CR_{PPI} \tag{20}$$

Where:

CR_{PPI} is the cost rate of post process inspection action, € per hour.

$T_{totalPPI}$ is the total time required to execute the post process inspection event.

$T_{transport\ QC}$ is the time required to take the units to CMM checks.

$T_{temp\ stabilisation}$ is the time required to stabilise the ambient temperature prior to the post process inspection.

$T_{scheduling}$ is the time required to schedule and organise for a part or a patch of parts to be inspected.

T_{report} is the time to report back to production manager.

And;

$$T_{totalPPI} = T_{transport\ QC} + T_{temp\ stabilisation} + T_{scheduling} + \left(T_{PPI} + T_{report}\right) * QV_{PPI\ number\ of\ parts} \tag{21}$$

Where, $QV_{PPI\ number\ of\ parts}$ is equal to one normally.

Combining equation (20) and equation (21) we get:

$$CV_{QC\ PPI} = \left(T_{transport\ QC} + T_{temp\ stabilisation} + T_{scheduling} + \left(T_{PPI} + T_{report}\right) * QV_{PPI\ number\ of\ parts}\right) * CR_{PPI} \tag{22}$$

Quality control time is one of the main elements of this cost function, due to the focus on machine and part accuracy.

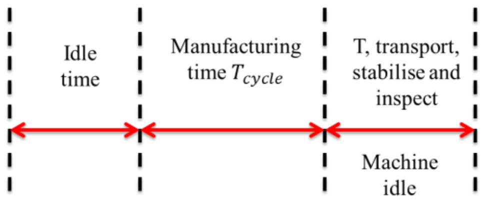

Fig. 5. Machine idle during post process inspection

It includes the cost of checking production parts (samples). The latency for quality control to detect non-conformance in produced parts includes the time for the part to travel to the inspection facility, the time to thermally stabilise, the time to measure (for example on a coordinate measuring machine (CMM)) and the time for the information to be fed back to the production manager in the form of a failure report.

$$CV_{QC\ reactive} = CV_{QC\ PPI\ confirm} + \left(CV_{QC\ PPI\ unmeasured} * QV_{unmeasured\ parts}\right) + CV_{QC\ MC\ error\ mapping} + CV_{MC\ verification} \tag{23}$$

$CV_{QC\ PPI\ confirm}$ is the cost of making a confirmation measurement in the event of finding a non-conforming part; upon finding a non-conformance the part might be re-inspected to confirm the results. $CV_{QC\ PPI\ confirm}$ can be equal to the normal cost of inspection, $CV_{QC\ PPI}$, or might differ if the confirmation process is a reduced subset of the overall measurements. The time for transportation $T_{transport\ QC}$ and/or part stabilisation, $T_{temp\ stabilisation}$, may be zero for the confirmation measurement if the part did not leave the inspection facility. Conversely, this time may be greater if the part has already moved on to another part of the manufacturing process, which might even involve being transported to another facility.

Therefore, to recheck the part or to confirm that the post process inspection of the part (Fig. 5) is correct the following equation is needed:

$$CV_{QC\ PPI\ confirm} = \left(T_{PPI} + T_{report}\right) * QV_{number\ of\ parts} * CR_{PPI} \tag{24}$$

If the inspection is done in batches then the time to transport, $T_{transport\ QC}$, and time for thermal stabilisation, $T_{temp\ stabilisation}$, will be unified across the batch, while $QV_{number\ of\ parts}$ is the number of parts in the batch. Otherwise, in the case where each part is individually transported, $QV_{number\ of\ parts}$=1.

In the event of detection of non-conformance, further quality control inspection may be required. Assuming that only a sample of parts are inspected, then referring to Fig. 3, the actual time t_2, where the machine went out of tolerance is not known. Therefore the parts that were not inspected between PPI_{n-1} and PPI_n should now be measured. The number of parts affected is given by equation (26). The cost of inspecting these “unmeasured” parts is given in equation (25), where $CV_{QC\ PPI}$ is given by equation (22). In this case, the values for transport and stabilisation time may vary from the regular inspection process since they will be diverted from their normal process flow.

$$CV_{QC\ PPI\ unmeasured} = CV_{QC\ PPI} * QV_{unmeasured\ parts} \tag{25}$$

$$QV_{unmeasured\ parts} = \left(\frac{t_3 - t_1}{T_{cycle}}\right) - 1 = \left(\frac{t_{PPIn} - t_{PPI(n-1)}}{T_{cycle}}\right) - 1 \tag{26}$$

3.5. MACHINE ERROR MAPPING

Machine error mapping is measuring the geometric errors of machine tools and coordinates measuring machines. The concept is based on classifying the machine error mapping into three stages as represented in equation (27). The cost of machine tool error mapping can be expressed as:

$$\begin{aligned} CV_{QC\ MC\ error\ mapping} &= CV_{preperation\ for\ machining\ part} + CV_{measurement\ of\ machine} \\ &+ CV_{startup\ after\ adjustment} \end{aligned} \tag{27}$$

Where:

$CV_{preperation\ for\ machining\ part}$; is the cost of preparation for machining a part after measurement given by equation (28).

$CV_{measurement\ of\ machine}$is the cost of machine measurement given by equation (32).

$CV_{startup\ after\ adjustment}$ is the inspection and adjustment needed even after machine full measurement to reach a machine stable production condition given by equation (36).

3.5.1. COST OF PREPARATION OF MACHINING A PART

$$\begin{aligned} CV_{preparation\ for\ machining\ part} &= T_{warmup\_adjustments\_reloading\ prog\_applying\ fix} \\ &* \left(CR_{adjustment\ service} + CR_{machine\ non-production}\right) \end{aligned} \tag{28}$$

Where:

$T_{warmup\_adjustments\_reloading\ prog\_applying\ fix}$ is the time required for machine warm-up, adjustments, reloading programs and applying any fixtures required prior to the manufacturing process.

$CR_{adjustment\ service}$ is the cost rate, € per hour of any adjustment services might be needed. This included the service workers and the hire of the equipment required (equation (29)).

For those manufacturing processes that require computer programming of the equipment as part of initial set-up to produce a new part, adjustment and programming time as well as establishing work-piece offsets must be included in the cost of machining a part preparation. Adjustments include the cost value needed for adjusting and modifying CNC codes and parameters.

$$CR_{adjustment\ service} = \sum_{i=1}^{n} CR_{i\ (adjustment\ service)} * QV_{i\ (adjustment\ service)} + \sum_{i=1}^{n} CR_{i\ (adjustment\ labour)} * QV_{i\ (adjustment\ labour)} \tag{29}$$

Substituting equation (7) and equation (29) into equation (28) gives:

$$CV_{preperation\ for\ machining\ part} = T_{adjustments\_reloading\ prog\_applying\ fix} * \left(\left(\sum_{i=1}^{n} CR_{i\ (adjustment\ service)} * QV_{i\ (adjustment\ service)} + \sum_{i=1}^{n} CR_{i\ (adjustment\ labour)} * QV_{i\ (adjustment\ labour)}\right) + CR_{burden} + CR_{idle\ labourer}\right) \tag{30}$$

Then:

$$CV_{reaction\ to\ detected\ non-conformance} = CV_{QC\ reactive} + CV_{machine\ non-production} * T_{investigation} + CR_{management} * T_{investigation} \tag{31}$$

The adjustment service hire cost per unit time is the rate for measurement and repair. This may include the daily rate expenses of labour travel, fuel and accommodation. The method of calculation differs depending upon the maintenance structure of the company. For instance, this cost should not be included in the final downtime cost calculation where a company has its own facilities and does not need to hire this service. In this case it is considered as a fixed cost. On the other hand, other companies need to hire this service, where it is probably being measured as a variable cost. Discussion of the relative merits of each approach is outside the scope of this paper, but is a fundamental management decision that must be made with a large number of other factors taken into account.

3.5.2. THE COST OF MACHINE MEASUREMENT

The cost of major machine tool measurement is not usually accounted as a prime cost, but as part of the burden or factory expenses cost of the total manufacturing cost. The same thing applies for indirect labour for measurement service, equipment installation, manufacturing equipment depreciation and energy costs. However, the cost of machine measurement is an element included in the main equation of the machine error mapping.

$$CV_{measurement\ of\ machine} = T_{measure} * \left(CR_{measurement\ service} + CR_{machine\ non-production}\right) \tag{32}$$

Where:

$T_{measure}$ is the time required to fully measure the machine tool.

$CR_{measurement\ service}$ is the cost € per hour of the measurement service. This is given by equation (33), where $CR_{measurement\ equipment}$ is the cost per hour of the measurement equipment and $CR_{measurement\ labour}$ the cost per hour of the measurement worker

And:

$$CR_{measurement\ service} = CR_{measurement\ equipment} + CR_{measurement\ labour} \tag{33}$$

Then:

$$CR_{measurement\ service} = \sum_{i=1}^{n} CR_{i\ (measurement\ equipment)} * QV_{i\ (measurement\ equipment)} + \sum_{i=1}^{n} CR_{i\ (measurement\ labour)} * QV_{i\ (measurement\ labour)} \tag{34}$$

Substituting equation (7) for $CR_{machine\ non-production}$:

$$CV_{measurement\ of\ machine} = T_{measure} * \left(\left(\sum_{i=1}^{n} CR_{i\ (measurement\ equipment)} * QV_{i\ (measurement\ equipment)} + \sum_{i=1}^{n} CR_{i\ (measurement\ labour)} * QV_{i\ (measurement\ labour)}\right) + CR_{burden} + CR_{idle\ labourer}\right) \tag{35}$$

3.5.3. COST OF PRODUCTION START-UP

The reason for performing machine error mapping is to establish the accuracy performance of the machine and, where necessary, use numerical compensation to make the machine as accurate as it is required to be. However, in this work it is assumed that even after measuring the machine there will be some inspection and adjustment needed and a low probability of producing scrap and rework parts; this assumption is reasonable, though it should be noted that it does not always hold true.

The time periods that contribute to the total time to machine a part are illustrated in Fig. 6, while actions between stopping and resuming production are shown in Fig. 7, Fig. 8. The cost due to the resetting and warm up period may include the cost of all scrap, rejects and adjustments until the machine settles down and reaches the steady state condition.

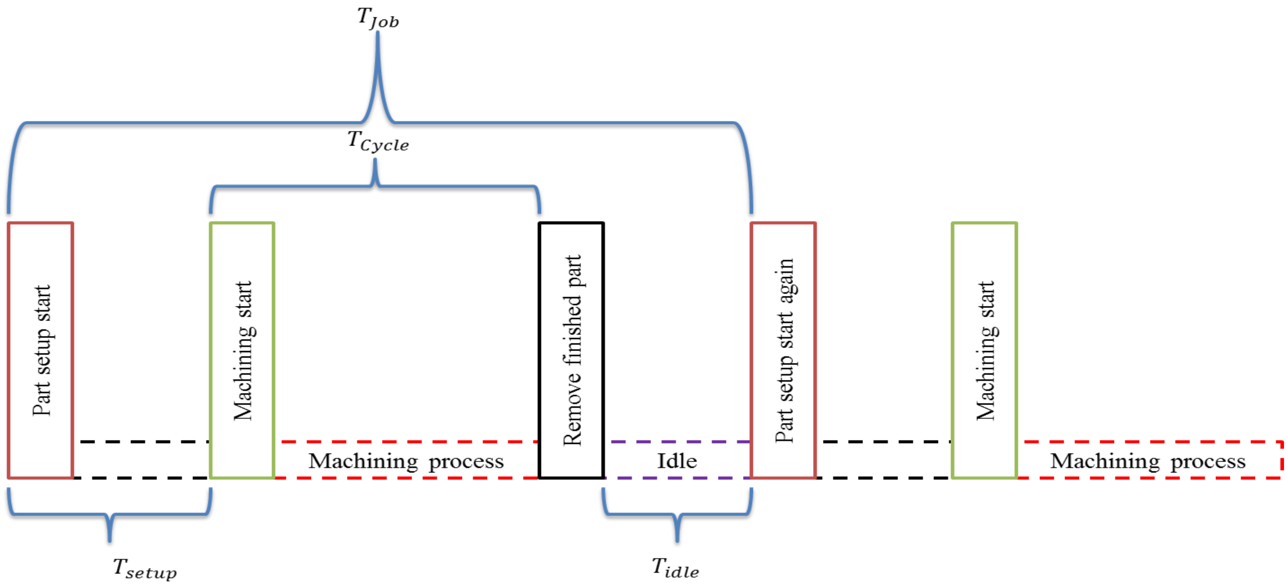

Fig. 6. Total time to machine a part

$$CV_{startup\ after\ adjustment} = CV_{reloading\ prog\ and\ reapplying\ fix} + CV_{scrap\ units\ startup} + CV_{rework\ units\ startup} + CV_{startup\ inspection} \tag{36}$$

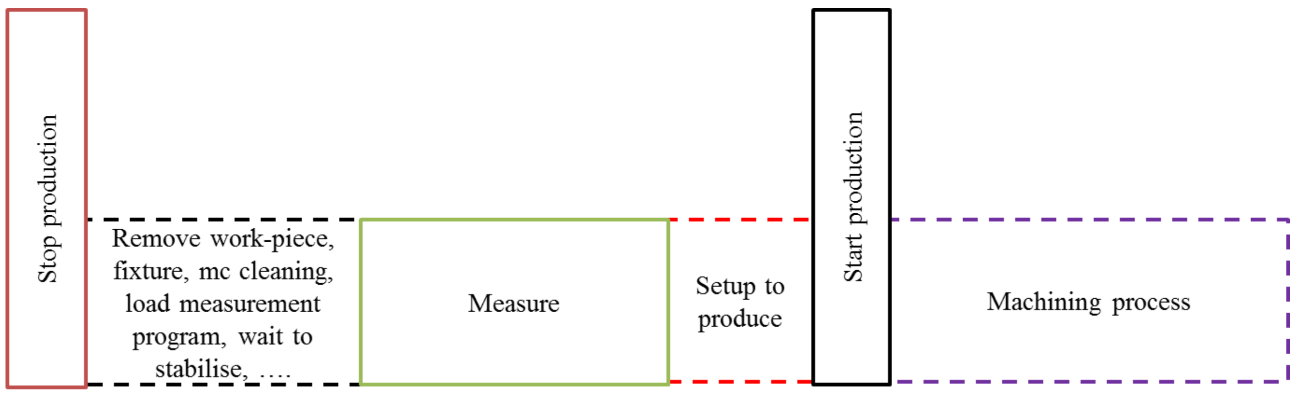

Fig. 7. Typical actions between stopping and resuming production

The setup time accounts for all the time spent repeating non-productive tasks that are necessary for the machining process, such as removing the finished work-piece, machine tool cleaning, modifying fixtures, loading control part program, warm-up cycles required to allow the machine to stabilise, measuring the machine etc.

From equation (12);

$$QV_{startup\ parts\ manufactured} = \frac{T_{idle\ waiting\ for\ PPI}}{T_{cycle}} \cong 1 \tag{37}$$

Where $QV_{startup\ parts\ manufactured}$ is normally equal to one, since it is good practise to validate the first part before proceeding to full production. In some circumstances a second part might be started before the results of the first have been achieved. This is running at risk, but is often applied where component value is low. The cost of start-up rejects will include the cost of all the parts rejected during the start-up period until the machine reaches steady state condition. Start-up cost per machine includes all the parts rejected during the start-up period until the machine reaches steady state condition, it also includes energy surge costs, set up (materials and manpower), percent of reduced production (units per hour lost), scrap produced includes rework, recycle costs and/or scrap value.

$T_{startup}$is equal to $T_{idle\ waiting\ for\ PPI}$ in this case, where the cost includes any scrap cost and additional inspection costs. This is to avoid any double counting of scrap and rework units during the production process.

From equation (13):

$$CV_{scrap\ units\ startup} = P_{scrap\ start\ up} * QV_{startup\ parts\ manufactured} * CV_{part} \tag{38}$$

$P_{scrap\ start\ up}$ is a lower probability of producing scrap units than in previous situation when producing parts in an uncontrolled period P_{scrap}.

Substituting equation (14) we get:

$$\begin{aligned} CV_{rework\ units\ startup} \\ &= P_{rework\ start\ up} * QV_{startup\ parts\ manufactured} \\ &* CR_{manufacturing} * T_{rework} \end{aligned} \tag{39}$$

Substituting equation (38) and equation (39) into equation (36) gives:

$$
\begin{aligned}
CV_{startup\ after\ adjustment} &= CV_{reloading\ prog\ and\ reapplying\ fix} + P_{scrap\ start\ up} \\
&* QV_{startup\ parts\ manufactured} * CV_{part} + P_{rework\ startup} \\
&* QV_{startup\ parts\ manufactured} * CR_{manufacturing} * T_{rework} \\
&+ CV_{startup\ inspection}
\end{aligned} \tag{40}
$$

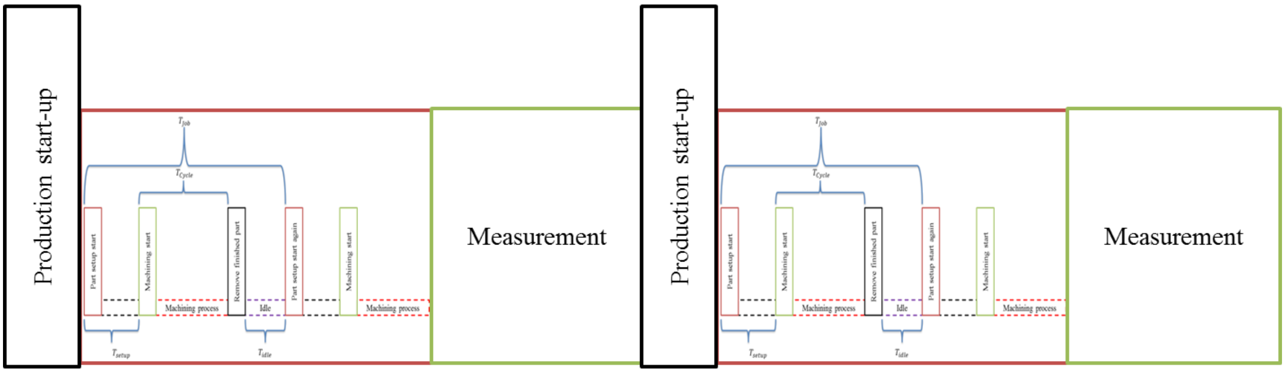

Fig. 8. Production start-up after machine measurement

This is sometimes called a pass off part process or a sacrificial part process. However, when producing a high value part this is not acceptable; advanced manufacturing is often striving for right-first-time.

3.6. TOTAL MACHINE TOOL ACCURACY RELATED COST

From equation (14) the cost value of uncontrolled production depends on the number of incidents. The quantity value of regular calibration is a variable that depends on the company decision of how many regular calibrations will be established. This is often a fixed value that is arbitrarily agreed. For example, annual error mapping of the machine is sometimes scheduled because it fits into other quality control systems.

Then the total cost of machine accuracy related cost can be represented as:

$$
\begin{aligned}
CV_{total\ accuracy\ related\ cost} &= CV_{Uncontrolled} + CV_{nonconforming\ parts\ customer\ impact} \\
&+ CV_{QC\ MC\ error\ mapping} * QV_{regual\ calibration} \\
&+ \left(CV_{QC\ IPI} * QV_{QC\ IPI\ parts} + CV_{QC\ MC\ verification} \right. \\
&\left. * QV_{QC\ MC\ validation\ checks}\right) \\
&+ CV_{reaction\ to\ detected\ non-conformance} \\
&* QV_{incidints\ of\ failures}
\end{aligned} \tag{41}
$$

Where the quantity of regular calibrations, $QV_{regual\,calibration}$, is the number of calibration actions taken per year. This value can be less than one if the actions are taken less than once per year.

A total cost of a reactive maintenance strategy in equation (18) is given by a modified form of equation (19) that includes the calibration of the machine after a non-conformance has been detected. In the case of no regular calibration, where the machine runs completely uncontrolled, the machine error mapping in the equation will be zero and the machine verification will cancel out.

If a regular calibration is always used and failures never occur then regular error mapping will be a value and the other terms of equation (19) will be assumed zero as no non-conformance parts are detected.

For simplification, the total cost of non-conformance could be represented as:

$$CV_{Total\,nonconformance} = \sum_{1}^{n} CV_{Uncontrolled} + \sum_{1}^{n} CV_{reaction\,to\,detected\,non-conformance} \tag{42}$$

Where:

$CV_{Total\,nonconformance}$ is the total cost incurred due to producing non-conforming parts.

Assume that all incidents are the same, then this can be simplified to:

$$CV_{Total\,nonconformance} = \sum_{1}^{n} CV_{Uncontrolled} + CV_{reaction\,to\,detected\,non-conformance} \tag{43}$$

From equation (19):

$$CV_{regular\,machine\,control} = \sum_{1}^{n} CV_{QC\,IPI} + CV_{QC\,MC\,error\,mapping} + CV_{QC\,MC\,verification} \tag{44}$$

Combining equation (43) and equation (44), equation (41) can be simplified to:

$$CV_{total\,accuracy\,related\,cost} = CV_{regular\,machine\,control} + CV_{Total\,nonconformance} \tag{45}$$

As more regular control is established, fewer non-conformances should be experienced and therefore fewer reactive actions are needed. The derived algorithm provides the balance between these two factors based upon known variables, estimated parameters and measurable performance.

4. DISCUSSIONS AND CONCLUSIONS

There is competitive pressure within manufacturing for higher production rates, tighter tolerances and reduced costs. A balance must be achieved between addressing these issues by proactive maintenance regimes and the negative impact that the predictive tasks will have on downtime of the machine. Machine tool accuracy is a key performance index for many high value machining companies. A conflict, which cannot be ignored, is that increasing speed of production can have an adverse effect upon the accuracy of the machine. Calibrating the machine regularly has a time penalty, but aims to produce better overall machine availability by reducing scrap and rework. Therefore, it can increase the effective operating time by eliminating wasteful non-productive time. The machine availability will have a great influence on having better overall performance efficiency and as a result a higher quality rate of parts will be produced. In other words, maintaining the machine regularly can increase the Overall Equipment Effectiveness (OEE).

One of the main contributing factors to the cost of a calibration is the downtime of the machine tool, which is often perceived as a non-value-added cost and therefore a barrier to implementing predictive calibration. To achieve an optimal, cost-effective maintenance approach, the analysis of failures and development and use of applicable mathematical cost algorithms is essential. The performance of a machine tool or group of machine tools depends not only on the design, layout and operation, but also on effective maintenance of the accuracy of the machines during their operational lifetime.

This paper primarily focuses on the creation and development of a novel methodology and a framework for determining the cost of maintaining the accuracy of machine tools, and the cost of non-conformance that would otherwise result. A significant part of the calculation is related to the machine tool downtime caused by planned or unplanned maintenance, loss of production and scrap/rework due to parts produced out of tolerance. This model can lead to better calibration decision-making on the relevance, or otherwise, of a PdC strategy and optimising the cycle of calibration process.

This model is not a once-only calculation; it will have to be repeated as variations in input costs such as energy prices, cost of raw materials, etc. influence the model parameters. The cost function could be used as a framework for tracking environmental “costs”, such as energy use and waste, in order to aid shop floor managers with determining the environmental impact of their operations.

Financial reductions could be achieved when using either preventive or reactive calibration strategies, depending upon the scale and value of the production. The algorithm derived in this paper can be used as a management tool to make the decision on the most appropriate strategy. Furthermore, it can be used to optimise the frequency of calibration actions that can reduce the predicted cost of preventative calibration to a similar amount to reactive calibration. An example case of the use of the algorithm is where small manufacturing company who produce reasonably high-value components could calculate that at their present production levels it is more cost effective to run to failure. However, a small rise in the input costs, which could come from the fluctuation in the material or energy markets, could made it to be more cost effective to maintain accuracy by regular machine calibration. Similarly, varying the inputs to the parameters can be used to evaluate other changes in scenarios, such as discovering if an increase in the volume of production will affect the decision on accuracy maintenance strategy.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1). The work is also partially supported by the European Commission project EASE-R3 (Grant Ref 608771/FP7-2013-NMP-ICT-FoF), for which the authors express their gratitude.

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