KES Transactions on Sustainable Design and Manufacturing I
Sustainable Design and Manufacturing 2014 : pp.83-94 : Paper sdm14-047

Towards an Optimization Calculation for Preventative and Reactive Calibration Strategies

Abubaker Shagluf, Simon Parkinson, Andrew P. Longstaff, Simon Fletcher

Centre for Precision Technologies, University of Huddersfield, HD1 3DH, UK
abubaker.shagluf@hud.ac.uk

Abstract Minimising manufacturing waste and reducing downtime are becoming increasingly important to industrial companies, especially those manufacturing with high levels of output or to a high level of accuracy, such as mobile phone, submarine, and aircraft. Increasingly, predictable output quality from machine tools relies on systematic calibration to improve and maintain their capabilities, as well as to reduce waste in terms of scrapped parts and energy from re-manufacturing. However, such calibrations remove the machine from normal manufacturing duties, which could have large financial implications.

This paper presents a cost optimisation process that is used to reduce unnecessary downtime while maintaining the machine at the required capability. The concept of this work will ultimately lead to a technically-driven management tool that can optimise the schedule of a calibration plan. In the paper we use a case study to validate the presented technique for both preventative and reactive calibration strategies. This case study shows that the calibration cost for both strategies can be decreased by intelligently reducing machine tool downtime. This results in the cost of using a preventative strategy being reduced, making it a commercially attractive alternative to reacting to failure, increasing the feasibility of using reactive calibration.

1. Introduction

Machine tools are electromechanically powered devices used during subtractive manufacturing to cut material. The design and configuration of a machine tool is chosen for a particular role and is different depending on the volume and complexity range of work-pieces [1]. A common factor throughout all configurations of machine tools is that they provide the mechanism to support and manoeuvre the relative position of the tool and the work-piece. For example, Figure 1 illustrates a three-axis machine tool consisting of three linear axes. More complex machines with additional rotary axes also allow change in relative orientation. The physical manner by which the machine moves is determined by its kinematic chain. The kinematic chain will typically constitute a combination of linear and rotary axes.

InImpact: The Journal of Innovation Impact | ISSN 2051-6002 | http://www.inimpact.org

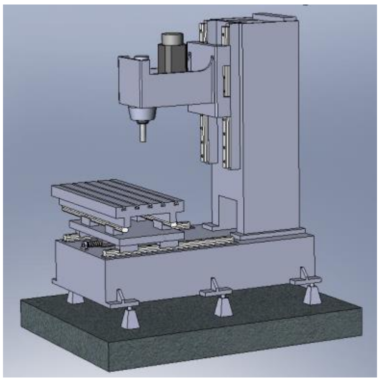

Figure 1: Three-axis machine tool

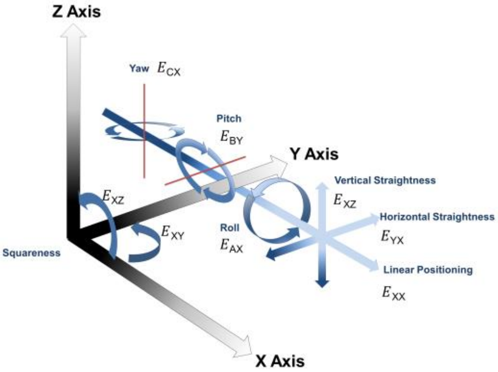

Figure 2: Linear motion errors

Predetermined machine tool movement can only be achieved by deterministic and controlled machine tool motion. Motion errors are deviations from the expected machine's tool path as a result of geometric errors in the movement of the machine tool's axes throughout the working volume. Figure 2 shows the motion errors of an axis of linear motion. In a perfect world, a machine tool would be able to move to predictable points in three-dimensional space, resulting in a machined artefact that is geometrically identical to the designed part. However, due to tolerances in the production of machine tools and the deterioration over time, this is very difficult to achieve.

Inaccuracy is present in all machines, but where this is too great, waste is generated in terms of scrapped parts and expelled energy and time during re-work. Machine tool calibration is the process of assessing a machine tool's manufacturing capabilities that includes error classification, measurement and analysis [2]. Performing a machine tool calibration contributes to the machine's accuracy by providing detailed analysis of the machine's geometric capabilities which can subsequently be used to determine corrective action, and provide confidence that a given asset is capable of machining a part within a predefined tolerance. A series of International standards exist for performing individual measurements correctly [3]. However, at present there is no standard way to plan a machine tool calibration and plans can be created *ad hoc* or in the order they were agreed previously. Non-optimal plans increase the cost of non-productive downtime [4].

Typically hourly rates for machine tools are estimated between £65 and £125 per hour. Justification is needed if this is spent in calibration rather than production. In this paper, two types of machine tool accuracy maintenance strategies are considered. The first is preventative calibration at a fixed rate [4] to ensure that the machine is producing parts with an acceptable tolerance, and the second is reactive calibration where the machine is calibrated only after non-conforming parts have been produced and identified [5].

The paper starts by providing the reader with an informative description of different machine tool calibration strategies. Following this, a model is described which can calculate the financial cost of preventative and reactive calibration. This motivates the use of a calibration downtime model to optimise the duration that the machine is unavailable for normal manufacturing operations using either strategy.

2. Machine Tool Calibration Strategies

A machine tool may often be calibrated throughout its working life. However, the frequency of calibration is dependent on the owner’s maintenance strategy, which often depends on their manufacturing capabilities. If a manufacturer is using a machine tool to mill items to large tolerances and the machine tool’s accuracy is diminishing slowly over time, then they might only need to calibrate their machine infrequently, perhaps biannually. However, if the same machine were used to produce parts to tight tolerances, the time taken for the machine‘s accuracy to drift out of tolerance would be reduced. In this paper, preventative and reactive calibration strategies are considered when manufacturing to various degrees of accuracy.

2.1. Reactive maintenance

Machine tool repairs are sometimes conducted only when the machine breaks down or otherwise fails to meet its key performance indices (KPI’s) [5]. The strategy is more “do not fix it until it breaks” than maintenance and is known as Corrective Maintenance (CM). Reactive calibration is a strategy where calibration is only carried out when quality control detects non-conformance of parts. This method is commonly used where high availability for production is required. It is also adopted when the components do not require high accuracy, understanding of machine errors is low, or the potential cost saving of calibration are not understood [6]. A reactive calibration strategy, as shown in Figure 3, can be cost effective in some cases. However, it can lead to scrapped parts, additional energy consumption during rework, and wasted diagnostic time. Reducing unexpected machine tool downtime and assuring quality is increasingly important as the demand for higher volume of production and “just in time” manufacturing has increased. Consequently, the adoption of periodic maintenance and calibration has evolved [5].

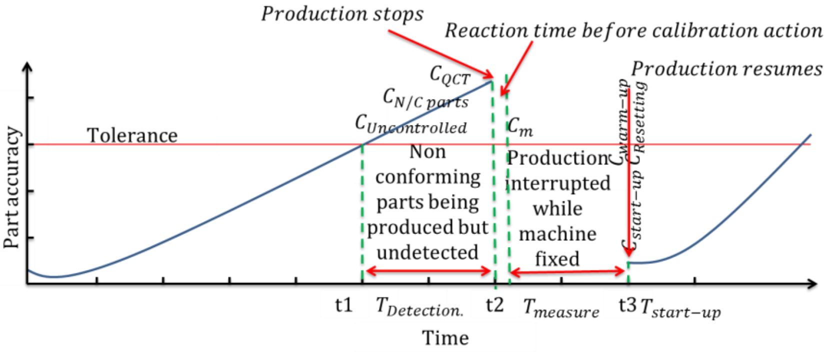

Figure 3 Machine tool run to fail scenario and the related costs.

2.2. Preventative maintenance

Preventive Maintenance (PM) and Preventive Calibration (PC) is a methodology where calibration is performed and parts are replaced before they fail, often using a probability model [7]. However, this technique can be wasteful since healthy parts will be discarded and downtime for replacement may not be optimised. Predictive Maintenance (Pd.M.) or Condition Based Maintenance (CBM) is a strategy that includes feedback of the instantaneous condition of the machine and detects degradation before a fault becomes critical [8].

Predictive Calibration (PdC) is a new methodology that can solve reactive calibration issues, proposed to be analogous with, or indeed a subset of, a Pd.M. strategy. It is intended to be a formalised approach applied to machine tools to measure and monitor any degradation in the mechanical parts to assist with maintaining the level of positioning accuracy, while having the added-value of revealing other maintenance issues such as wear in ball-screws, guide-ways, impending bearing failure, etc. Although inspired by Pd.M., accuracy is difficult to monitor “live” with available technology so a periodic approach is required [9]. It is therefore necessary to apply the necessary technical knowledge along with management strategies and decision making skills [10].

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. 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 [6].

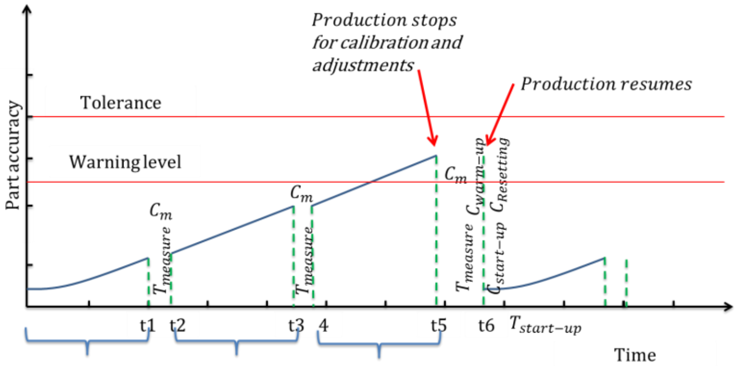

Figure 4 Preventative calibration and adjustments at fixed rate

3. Calculating Calibration Cost

This section of the paper describes a universal mathematical cost function that forms the basis of a strategy for scheduling machine tool calibration. The cost function is based on a process that takes into account a number of variables such as maintenance service hire cost per unit time, part volume, production volume, etc. The following list provides an explanation of the factors considered in this paper. A comprehensive explanation of them can be found in Shagluf et al [4, 6].

1. C_m, Cost of performing the measurements.
2. $C_{warm-up}$, Cost of performing a warm-up cycle, typically including any pre-machining checks.
3. $T_{start-up}$, is the start-up time for a machine to reach a stable condition.
4. $C_{Uncontrolled}$, Cost of uncontrolled production where the machine is producing non-conforming parts.
5. C_{QCT}, Quality control cost
6. $C_{N/C\,parts}$, Cost of the non-conformance parts.

Using these factors, the following equation can then be used to produce a cost of performing the calibration.

$$C_{down-time} = C_m + C_{warm-up} + C_{start-up} + C_{Uncontrolled} + C_{QCT} + C_{N/C\,parts}$$

Using this equation will result in an estimated calibration cost, which considers both the contribution of technical and commercial factors. The cost function produced will help with optimising the machine tool calibration procedure. This will also benefit the decision making process, which also aims to improve machine's availability and promote performance stability. The cost of downtime evaluation is a technical-driven management tool towards optimising the intervals between calibrations.

4. Reducing Downtime

As described in the previous section, the cost of the machine downtime during the calibration (C_m) is important when calculating the overall cost of the calibration. However, further refinement can take place to optimise a calibration plan to reduce downtime based on the specifics of the measurements. A calibration plan is a sequence of measurements where each measurement has many factors that have temporal influences. The following list contains the factors that are used for temporal optimisation in this paper.

1. **Set-up**: The duration required to set-up the instrumentation.
2. **Measurement**: the duration required to perform the measurement and acquire the data.
3. **Adjust error being measured**: The duration required if a measurement set-up can be adjusted to test for another error.
4. **Adjust position**: The duration required if a set-up needs to be adjusted to measure another portion of the error. This can occur when measuring an axis with a travel that is greater than the range of the instrument.
5. **Removal**: The duration required for removing the instrumentation and storing it away.

Based on these temporal factors, it is possible to intelligently select and schedule the instrumentation and test method for each error component with the optimisation criteria of reducing a machine's downtime. In addition, it is possible to consider the use of concurrent measurements, thus further reducing downtime. However, this relies on expert knowledge to demine any effect on the measurement's quality.

A three-axis machine tool has a total of twenty-one possible motion error components which each require measuring. In the first instance twenty-one measurements may appear to present very little planning challenge. However, there are more 5×10^{19} permutations. Naturally, this increases as the number of axes, and so number of error sources, increases. Identifying the optimum sequence of measurements can be solved using a computational search algorithm.

Advancements from classical planning to include representation of durations and resources are required to solve this challenge [11]. A classical planning problem uses a restricted state-transition system which is defined as a triple $P = (\sum, s_0, g)$ where s_0 is the initial state and g is the set of goal states. A solution P is a sequence of actions $(a_1, a_2, \dots, a_k)$ corresponding to a sequence of state transitions $(s_1, s_2, \dots, s_k)$ such that $s_1 = \rightarrow (s_0, a_1), \dots, s_k = \rightarrow (s_{k-1}, a_k)$ and s_k is the goal state.

In the proposed model, s_0 that represents the state of the machine tool and instrumentation, a required goal state, g, indicating all the measurements that are required, and a solution, P, containing a sequence of actions. The addition of time and resources is essential for modelling machine tool calibration. The produced model is non-deterministic in that there are one or more actions from each state. This increases the state space size and makes the problem more difficult to solve. However, introducing a duration for each action provides the possibility of using temporal optimisation heuristics, such as those implemented in the chosen planner, LPG-td [12].

In the model, many potential aspects that can decrease duration have been encoded. For example, sequentially scheduling measurements using the same instrumentation can reduce measurement set-up time because the instrument has already stabilised to the environmental conditions or any self-heating effects. Another consideration in the model is the ability to perform measurements concurrently. This can result in a large reduction in downtime, but it is only possibly if the measurements are compatible and do not interfere.

In this paper, a previously developed and validated model to search for an optimal calibration plan [13, 14] is implemented. The model is written in the Planning Domain Definition Language v2.2 (PDDL) [15] which is standardized throughout the discipline of domain-independent artificial intelligence planning allowing for the expression of time and resources. Using this language allows the model to be used and solved using LPG-td which is a state-of-the-art planning tool [12] to produce optimum measurement schedules. In addition, the schedules can be validated alongside the model using a tool such as VAL [16].

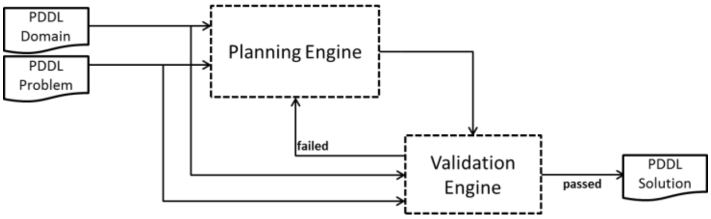

Figure 5: Schematic of implementation

Figure 5 shows the schematic for the implemented system which takes two PDDL files as input. The first is the domain model and the second is the problem definition file. The planning engine searches for an optimal solution within a given time frame and is subsequently validated against the domain model and the problem instance. This ensures that the calibration plan satisfies all the required constraints. The produced PDDL solution contains an optimum permutation of measurements to perform a full machine tool calibration. The downtime of the solution is optimised in terms of instrumentation selection and scheduling.

5. Case Study

In Figure 3 and Figure 4, the machine is unusable for production for the duration of the calibration (C_m). Therefore, while ensuring no compromise in the exactness of the calibration, minimising C_m is beneficial for manufacturing since the machine can return to production as quickly as possible. In this section, a case study is provided to investigate the effect of reducing the calibration cost for both reactive and predictive calibration strategies for a five-axis machine tool. This case study involves comparing the calibration costs when using a calibration plan produced by an expert against one produced by using automated planning.

To demonstrate the presented technique of minimising C_m using artificial intelligence planning [13], the duration of a calibration plan for an industrial expert is compared with the calibration plan from using automated planning. A full comparison can be found in Parkinson et al [14].

Table 1 shows the durations for calibrating the machine using a plan devised by a human expert and that from the proposed technique. It also shows the different between maximising and minimising the duration when using automated planning; the maximum value is a possible, though unlikely “worst case” scenario. The automated planning method provides a gain of approximately one hour over the expert’s plan, and more than four hours over the worst case. These savings become more significant when multiplied over a number of machines and when considering the cumulative effect if calibration is to take place on a regular basis.

Method	**Duration in hours**
Industrial Expert	12:30
Automated Planning – maximise duration	15:42
Automated Planning – minimise duration	11:18

Table 1: Downtime reduction using automated planning

In Figure 6, an excerpt from a plan with a maximized duration can be seen. In this figure it is noticeable that both the order and instrumentation selection are not optimized. Conversely, In Figure 7, a plan excerpt from the automated plan is presented where the error components in the direction of the X-axis are scheduled. In the figure it is noticeable that the measurements are scheduled where the same instrumentation can be used for different measurements, and where concurrent measurements can be performed.

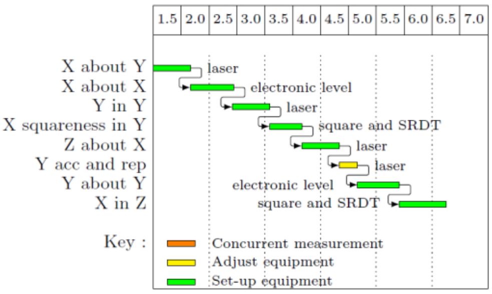

Figure 6: Maximized plan excerpt

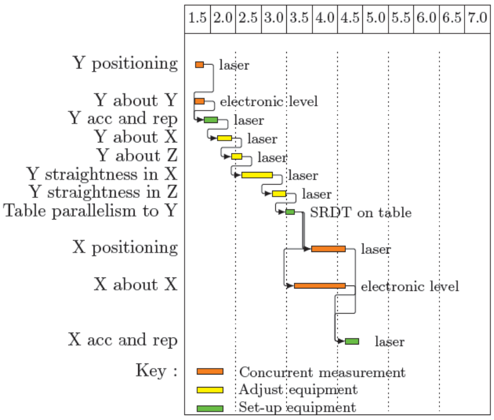

Figure 7: Minimized plan excerpt

In the case study, the preventative calibration strategy schedules five calibrations. The following assumptions are made:

1. A warm up cycle ($C_{warm-up}$) of 1 hour is required after any calibration. This might include any needed pre-machining checks and adjustments.
2. A start-up period ($T_{start-up}$) of 30 minutes is required after any failure. This figure is quite conservative.
3. An aerospace component with cost of £10 and a production of 10 parts per hour are assumed so the production loss will be £100 per hour.
4. The time ($C_{Uncontrolled}$) to detect that non-conforming parts are being produced is 15 hours. This represents the time taken to transport the parts to a quality control (QC) department, for their measurements to be scheduled and the report to be issued to production. Of course, this length of time is highly dependent upon the QC method employed.
5. The raw material cost and the cost of previous machining operations on the part prior to the machine is assumed to be £15.
6. A reaction time of 8 hours between detection of failure and the ability to begin the unplanned measurement. This is comparable with a 24 hour response-time service contract. The cost due to producing non-conforming part ($C_{N/C\,parts}$) which may include losing contracts due to reputational harm because of customer dissatisfaction is assumed to be £3000. This may include fines, shipping costs, etc.
7. The cost of hiring of measurement equipment is a direct cost. Labour cost is assumed to be £15 per hour.
8. There are two episodes of non-conformance within the 5-year period.

Table 2 shows the expert generated calibration cost and the cost for both preventative and reactive strategies. Additionally the table also shows the cost when optimizing the calibration plan. The reactive calibration assumes two calibrations in five years (after each non-conformance episode), whereas the preventative assumes five calibrations in five years. From this table, it is evident that there is a £276 reduction in estimated calibration cost for reactive calibration and a £690 for the preventive strategy. The impact of using the cost reduction technique is illustrated in Figure 8.

	Expert Generated		Optimised	
Cost Factors	**Preventative**	**Reactive**	**Preventative**	**Reactive**
C_m	71787	2875	6498	2599
$C_{warm-up}$	560	224	560	224
$C_{start-up}$	0	100	0	100
$C_{Uncontrolled}$	0	3000	0	3000
C_{QCT}	0	1600	0	1600
$C_{N/C\,parts}$	0	6000	0	6000
$C_{down-time}$	7747	13799	7057	13523

Table 2: Estimated calibration cost in £ for expert generated and optimised preventative calibration strategies

Figure 8 shows the above values, but also the scenario if there is only a single non-conformance event within the case study period. In this situation, the optimized process brings the difference between a reactive and predictive calibration strategy to less than £300, not including equipment costs.

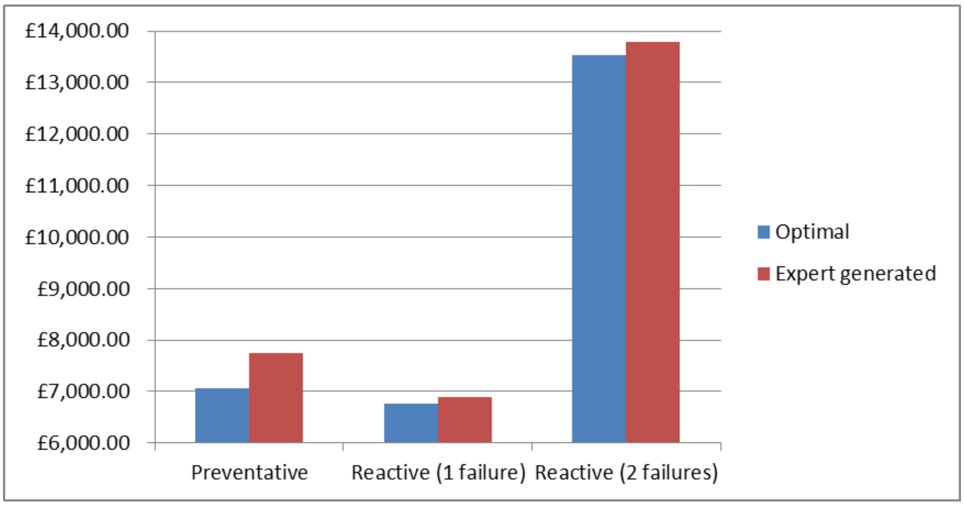

Figure 8: Graph showing reduction due to optimisation process

6. Conclusion

Waste in manufacturing has a significant impact on the environmental sustainability of manufacturing facilities. Scrapped raw materials, energy and consumables during re-machining all have a negative impact on the environment. In this paper, the requirement to calibrate machine tools to maintain their accuracy and minimizing manufacturing waste has been discussed. Following this, a discussion into preventative and reactive calibration strategies is presented, identifying that both strategies can have significant financial implications. This resulted in the development of a method to estimate the cost of both predictive and reactive machine tool calibration.

One of the main contributing factors to the cost of a calibration is the downtime of the machine tool, which is often perceived to be a barrier to implementing predictive calibration. A machine tool downtime reduction model using artificial intelligence planning is proposed. This approach allows for expert knowledge to be encoded and produce optimal calibration plans. This technique will intelligently schedule measurements that can utilize the same instrumentation sequentially, and where possible, schedule compatible measurements simultaneously.

The presented case study showed that financial reductions can be achieved when using both preventive and reactive calibration strategies. More importantly, the case study illustrated how optimizing the duration to perform a calibration can reduce the cost of preventative calibration to a similar amount to reactive calibration with a single non-conformance event, making the former more palatable in a production environment. The case where more than one event occurs shows even greater benefit.

The work presented in the paper, and the case study, verify the use of such techniques and it is intended that they will lead to a calculator that can predict benefits of such a regime based upon different volumes and value of manufacturing. Further case studies will be produced to cover this broader range of scenarios.

Acknowledgement

The authors gratefully acknowledge the UK's Engineering and Physical Science Research Council (EPSRC) funding of the EPRSC Centre for Innovative Manufacturing in Advance Metrology (Grant Ref:EP/I033424/1).

References

[1] T. Moriwaki, "Multi-functional machine tool," CIRP Annals-Manufacturing Technology, vol. 57, pp. 736-749, 2008.
[2] H. Schwenke, et al., "Geometric error measurement and compensation of machines—an update," CIRP Annals-Manufacturing Technology, vol. 57, pp. 660-675, 2008.
[3] ISO, "Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions," ed. Geneva, Switzerland: ISO, 2012.
[4] A. Shagluf, et al., "Towards a Downtime Cost Function to Optimise Machine Tool Calibration Schedules," Advanced Manufacturing Engineering and Technologies NEWTECH 2013 Stockholm, Sweden 27-30 October 2013, p. 231, 2013.
[5] C. K. Mechefske, "Machine Condition Monitoring and Fault Diagnostics," in Vibration an d shock Handbook, C. W. d. Silva, Ed., ed. Boca Raton: CRC press, Taylor and Francis Group, 2005, p. 35.
[6] A. Shagluf, et al., "The Importance of Assessing Downtime Cost Related Factors Towards an Optimised Machine Tool Calibration Schedule," presented at the Computing and Engineering Annular Researchers' Conference 2013 (CEARC'13), Huddersfield, UK, 2013.
[7] Y.-S. Shum and D.-C. Gong, "Development Of A Preventive Maintenance Analytic Model," in Fifth Asia Pacific Industrial and Management Systems Conference, Gold Coast Australia, 2004, pp. 38.5.1-38.5.12.
[8] L. Bin, et al., "Predictive maintenance techniques," IEEE Industry Applications Magazine, vol. 15, pp. 52-60, 2009.
[9] A. Shagluf, et al., "Predictive Calibration-Based Tolerance Boundaries For Arresting Deterioration of Machine Tool Accuracy," presented at the 2nd Annual EPSRC Manufacturing the Future Conference, Cranfield University, UK, 2013.
[10] F. Moe, et al., "Predictive Maintenance and Diagnostics of Machine Tools.," presented at the Virtual International Conference on Innovative Production Machines and Systems (IPROMS), Berlin, 2008.
[11] M. Ghallab, et al., Automated Planning: Theory & Practice: Elsevier Science, 2004.
[12] A. Gerevini, et al., "An Approach to Temporal Planning and Scheduling in Domains with Predictable Exogenous Events," J. Artif. Intell. Res.(JAIR), vol. 25, pp. 187-231, 2006.
[13] S. Parkinson, et al., "The Application of Automated Planning to Machine Tool Calibration," in ICAPS, 2012.
[14] S. Parkinson, et al., "Automatic planning for machine tool calibration: A case study," Expert Systems with Applications, 2012.
[15] M. Fox and D. Long, "PDDL2. 1: An Extension to PDDL for Expressing Temporal Planning Domains," J. Artif. Intell. Res.(JAIR), vol. 20, pp. 61-124, 2003.
[16] R. Howey, et al., "VAL: Automatic plan validation, continuous effects and mixed initiative planning using PDDL," in Tools with Artificial Intelligence, 2004. ICTAI 2004. 16th IEEE International Conference on, 2004, pp. 294-301.