

# Survival of the fittest - the process control imperative

## Abstract

In the face of international rivals, manufacturers need to constantly focus on their operating margins if they are to remain competitive. But what is the best way to tackle waste and boost profits? This paper explores four areas in which substantial productivity gains can be made if firms are prepared to change the way they control their machining process.

## Where are the opportunities to boost margins?

Competitiveness ultimately comes down to a combination of cost, quality, and service. To boost our competitiveness, therefore, we need to:

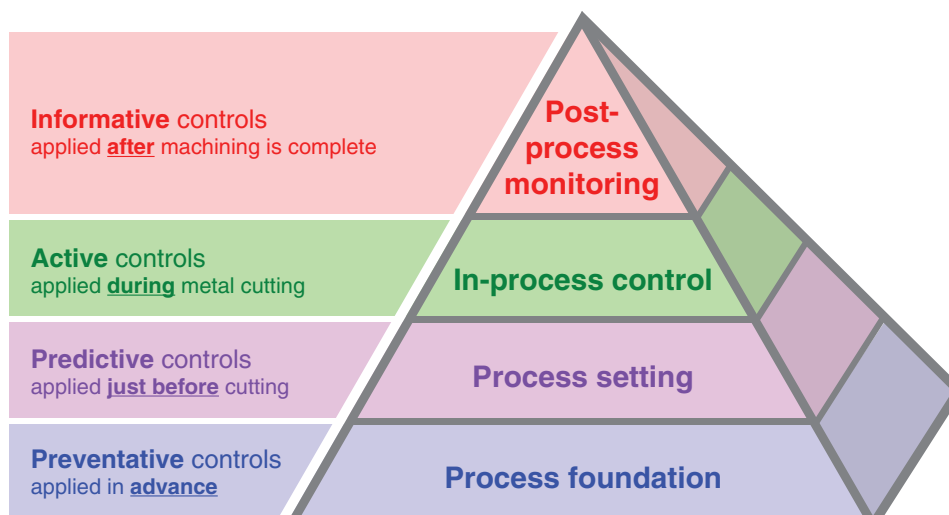
- Achieve more throughput from our assets
- Increase automation and reduce human intervention
- Reduce scrap, rework, re-makes and concessions
- Shorten manufacturing lead times
- Increase process capability and traceability

These goals demand a comprehensive approach to process improvement. Eliminating operator intervention is an obvious place to start, as human error is the major source of delay and non-conformance in many factories. But removing manual processes is not enough - we also need to pay close attention to the operating environment, the machine itself, setting processes before we start cutting, and in-process controls once production starts. This paper outlines a simple model that explains the sources of process non-conformance and process control methods to address them.

## Lean can only take you so far

Lean manufacturing techniques help manufacturers to streamline the flow of work through their factories, eliminating waste, reducing lead times and minimising work in progress. These are valuable savings, but they only work well if the machining process itself is predictable, repeatable and reliably producing conforming parts. In the absence of this, bottlenecks, delays and poor deliveries are impossible to eliminate.

The key to predictable productivity is, therefore, to tackle variation at source, isolating the root causes and addressing them individually. As each underlying source of variation is addressed, it makes the task of controlling the output of the process that much simpler.



*The Productive Process Pyramid™ shows how layers of control can be used to systematically remove variation from machining processes.*

## The Productive Process Pyramid™

The Pyramid comprises four layers of process control which build upon one another and which must each be brought to bear to deliver regularly conforming parts. Starting at the bottom:

- The **process foundation** layer is about providing stable conditions in which the machine can do its work. These are preventative controls that reduce the number of sources of variation before machining starts.
- Next up is the **process setting** layer, which deals with predictable sources of variation such as the location of the part, the size of the tools and offsets on the machine tool that could otherwise cause the first part to be non-conforming.
- The third layer is **in-process control**. This tackles sources of variation that are inherent to machining - tool wear and temperature variation - providing intelligent feedback to the process as metal cutting proceeds.
- Finally we reach the **post-process monitoring** layer, in which firstly the process and ultimately the part are checked against their respective specifications. Aspects of this can be done on the machine, but most tasks are done offline.

If high process capability and predictable productivity are the goals, then the best approach is to work from the bottom up through these layers. At the base of the Pyramid, the tasks are more generic and so can easily be applied broadly. As we progress up through the layers, the controls become more process-specific and hence their scope narrows. It therefore makes sense to apply these narrower controls only once the underlying variation has been addressed, or the return on this investment will be diluted.

Let's look at each layer in turn in a bit more detail.

### Process foundation

Controls in the base layer of the Pyramid are targeted at maximising the stability of the environment in which the process is to be performed. These preventative controls stop special causes of variation having an impact on the machining process.

Controls in the process foundation layer include:

- Design for manufacture - an approach to product and process design based on a thorough understanding of current capability and a drive towards best practice rather than 'reinvention of the wheel'. Often based around a 'standard features' approach, it involves rationalisation of tooling and standardisation of machining parameters. Its effect is to reduce the variation between processes and enable engineers to make far-reaching improvements when new best practice is identified
- Control of process inputs involves the use of FMEA and similar techniques to understand and control all the upstream factors that can affect machining process outcomes. This can include ensuring consistent cutter geometry, controlling clamping forces, locking down part programs and billet preparation. If conditions are consistent at the start of the process, they are more likely to be consistent at the end
- Environmental stability addresses those external sources of non-conformance that cannot be eliminated in advance, but which are inherent to the operating environment. These include ambient temperature variation, heat generated whilst machining, machine and fixture cleanliness, tool life management as well as unexpected events such as tool breakage and power outages. The solution for many of these variation problems is through operating disciplines
- Machine condition optimisation is an essential element of the process foundation, as an inaccurate machine cannot make consistently accurate parts. A rigorous process of performance assessment, calibration and (where required) refurbishment can bring the machine's performance in line with the process requirements. Thereafter a regime of regular operator-driven conditioning monitoring checks can be used to confirm the machine's ongoing suitability for production, or highlight the need for maintenance intervention.



Calibrating a machine with a laser interferometer

The process foundation layer boosts margins through:

- **Increased machine availability** - avoid unplanned downtime by tracking machine performance trends before they cause process problems
- **Increased process capability** - with better machine accuracy and repeatability, combined with less variation from the environment and process inputs, parts will be more consistent and non-conformance will be reduced
- **Guaranteed quality** - with less part-to-part variation scrap, rework and concessions are all reduced, typically by 25%
- **Focussing engineering on proactive tasks** - with less 'noise' to deal with, engineers can stop fire fighting and start to make lasting improvements

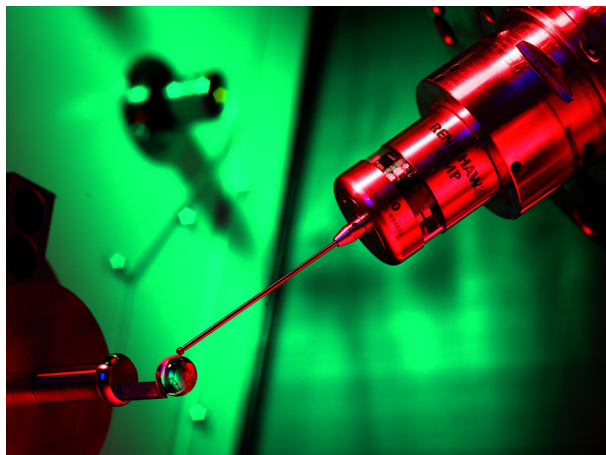
All this builds a foundation for automation - with your machines performing at their optimum, you can confidently take steps to automate your processes

### Process setting

The second Pyramid layer contains the first of these steps towards a 'green button' process and deals with getting ready to machine. These predictive controls tackle sources of error in the set-up of the machine, part, tool and probe that are always present to varying degrees and which must be dealt with if the first component is to be machined correctly. Building on the stability introduced by the process foundation layer, process setting controls help to eliminate human error by automating manual processes.

Controls in the process setting layer include:

- **Machine setting** is often overlooked and involves establishing the relationships between key moving elements of the machine (e.g. the milling spindle to the machine bed, or the pivot point of the milling spindle on a mill-turn machine). These relationships are affected by thermal drift and some variation is inherent in even the most stable environment. Uncorrected machine errors can be the dominant factor in process non-conformance and may lead to extended setting times as their effects can easily be confused with other sources of process variation. The good news is that these errors can be measured and eliminated by simple on-machine probing checks.
- **Probe setting** is the process of datuming a probe so that it can be used to measure accurately on the machine. For inspection probes, this involves measuring the size and position of the stylus typically using a datum sphere or ring gauge. For tool setting probes, a tool arbour is used to establish the position of the stylus or laser beam. Probe calibration is a regular (typically weekly) control that ensures other measurements on the machine remain reliable.
- **Part setting** is the process whereby the location and orientation of the component are established so that machining can be aligned with it. A touch probe can be used to find datum positions and angles, with work co-ordinates being updated automatically. In more complex situations, a probe can measure local surface forms so that a CAM package can compute tool paths to blend surfaces. Part setting reduces fixture costs, eliminates the need for operator intervention, and limits the scope for setting machining off on the wrong foot.
- The final element is **tool setting**, where the length and diameter of tools are established and stored in the CNC. This means that tools can be introduced to the part and cut close to nominal, avoiding manual 'cut and measure' activities and operator errors whilst keying height offsets - a major source of crashes in many shops.



*Establishing the pivot point of the milling spindle on a mill-turn machine*

The profit impacts of the process setting layer are:

- Part and tool setting **reduce setting times by up to 90%**
- Probing is **automated** and **more repeatable** than manual methods
- A more reliable setting process means **less downtime** once production starts
- When tools are replaced, **re-setting** will also be faster and less error-prone
- All this leaves you with **more time to make parts**

### In-process control

This layer is often the least exploited and least well understood. These controls tackle the inherent sources of variation in all machining processes - namely tool wear, part deflection and the impact of temperature and heat flows. On-machine probing is the only cost-effective way to monitor the in-process state of the component, and gives the machine the intelligence it needs to make its own decisions, constantly centring the process and eliminating the adverse effects of process drift. The result is a consistently capable 'green button' process that requires less manpower and results in less rework and scrap.

Before going any further, it must be stressed that in-process control can only be successfully implemented if the lower Pyramid layers are in place. If these other sources of variation are not under control, then in-process control will be fighting an uphill battle against random forces that it is not equipped to tackle. Attempting to automate a process in a chaotic environment with unreformed manual processes is folly.

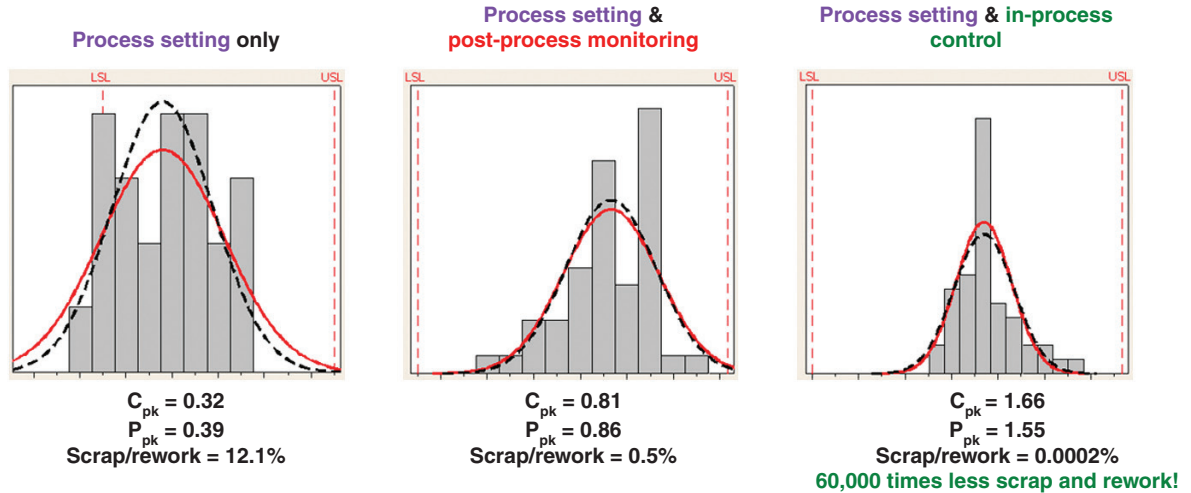
So what sorts of controls are involved in this layer?

- There is no point measuring every feature on the part if they are all made with just a few tools. A better approach is to spend as little time as possible checking a **critical feature for each tool** using a touch probe, and updating the tool offsets from the errors that you measure. An inspection probe is the way to control tools once cutting has started, not a tool setter, as it directly measures the output that you want to control - the size that the tool is cutting
- **Control roughing tools**, not just finishing tools. Although unseen by post-process inspection, roughing tools perform a vital task: leaving the correct amount of material for the finishing tool to remove. If the rough feature is inconsistent, then the finishing cut depth will also vary, affecting tool deflection and surface finish
- **Monitor thermal drift** by re-datuming the spindle position, rotary table centre-lines or pivot points at regular intervals, especially before critical finishing operations
- **Check delicate tools** for breakage after each cutting cycle to ensure that a single broken tool does not result in further damage to tools and parts. This increases confidence in unmanned machining.
- **Put logic in the program** to react to unexpected events. If parts are out of tolerance but with metal on, then call up another finishing pass. If a tool breaks, call up a sister tool or alert the operator. Don't accept a bad result at face value - wash the part and re-measure to ensure you're not probing on swarf
- **Monitor the process status** and alert the operator if errors occur
- Store in-process measurements and offset updates for subsequent **traceability**

In many circumstances, in-process control can yield the highest profit gains of any of the Pyramid layers, particularly if processes involve high levels of tool wear and extended cycle times:

- **Reduced capital costs** - increase throughput without investment in new capacity
- **Increased automation** - reduced direct labour costs and unproductive machine downtime
- **Reduced human error** - repeatable measurement and automated feedback
- **Less scrap, rework and concessions** - less variation, higher process capability and 'right first time'





Results of a capability study conducted at Renishaw on the same parts using different process control techniques. With just process setting, scrap levels are unacceptable and process centring is poor. Post-process monitoring with adjustment of the finish cut gives improved centring and reduced part-to-part variation, but results in capabilities that are below acceptable levels for most firms. Only intelligent in-process control, in which both rough and finish tools are controlled in-cycle, yields the level of capability that Renishaw finds acceptable and which permits extensive periods of unmanned operation.

### Post-process monitoring

The top layer of the Pyramid is well used by many firms as it provides the final assessment of process outcomes. Verification can be performed on the machine tool itself using a probe, at the machine using hand gauges or articulating arms, or on a CNC offline device such as a CMM. These are informative controls, as the measurements are too late to influence the component being measured unless a rework process is called up.

Controls in the post-processing monitoring layer are:

- On-machine process verification using a probe to measure features on the part whilst it is still in the machining fixture. Checking the part before it is moved, essentially verifying that the process has performed as expected, gives confidence about the part's conformance prior to any further operations. This approach makes most sense of large, high-value parts. It is also possible to perform 'CMM style' checks on parts, including geometric dimensions and tolerances, although the precision and traceability of machine tool measurements will be lower than those on a CMM under controlled temperature conditions. It may not be possible to access some datum features whilst the part is in the machining fixture. Also the cycle times on CMMs equipped with the latest measurement technologies will typically be much shorter.



Rapid inspection of high volume parts using an Equator™ versatile gauge

- Off-line part verification, featuring full inspection against the specification, typically using a CMM or gauge. CMMs have the advantage over on-machine techniques of offering 3- and 5-axis scanning technologies that enable faster and more comprehensive measurement of complex shapes, as well as sophisticated analysis and reporting. CMMs are often used in temperature controlled environments to provide greater accuracy. A new generation of versatile gauges provides rapid comparative part measurement on the shop floor to enable immediate process feedback. In both cases, measurement results and point data can also be stored for long-term traceability

New solutions such as REVO® 5-axis scanning and Equator™ versatile gauging technologies offer productivity benefits compared to conventional post-process inspection techniques:

- Radically faster CMM measurement yielding greater throughput without compromising accuracy
- Reduced manpower due to full automation of complex measurement tasks
- Multi-sensor platform (REVO®), enabling the automation of other verification processes such as surface finish measurement
- Flexible measurement of features in all orientations with infinite positioning
- Lower capital expenditure due to short cycle times and reduced need for rotary tables
- Reduced gauging costs compared to traditional custom gauges

### Profit impact examples

Let's look at an example of the impact of improvements in process control on a machining process. In this case study, the part is a relatively high value aerospace component:

Machine capital cost	£500,000	per machine
CMM capital cost	£120,000	per CMM
Depreciation period	10	years
M/C hourly rate	£75	per hour
CMM hourly rate	£75	per hour
Planned time	120	hours / wk
M/C operator manning level	1.0	operators per shift per machine
CMM operator manning level	1.5	operators per shift per CMM
Operator costs	£35,000	per operator per year
Material costs	£5,000	per component
Cutting cycle time	30.0	hours
Rework cutting time	2.0	hours
CMM cycle time	7.0	hours
M/C to CMM ratio	2.0	machine tools per CMM
Cost per concession	£500	ME costs

### Manufacturing Data

The current process outcomes, measured using Overall Equipment Effectiveness (OEE), where the quality measure assesses the first time pass rate, are:

Productivity		
Current OEE	53.0%	
Availability	85.0%	
Performance	80.0%	
Quality	78.0%	first time pass rate
Rework rate	10.0%	including reworked parts
Scrap rate	2.0%	including reworked parts
Concession rate	10.0%	including reworked parts

From these data, we can compute the number of parts made each year, the level of scrap, rework and concessions.

<b>Output per machine</b>	
Parts processed	141
Reworked parts	14
Scrap parts	3
Concessions	14
Conforming parts	<b>124</b>
Supplied parts	<b>138</b>

The value added is computed from the number of parts supplied (including concessions) multiplied by the standard hours and the hourly rate. From this we subtract the labour costs, depreciation and quality costs to compute the 'margin' that the machine contributes (note that this figure does not include consumables and other variable costs):

<b>Margin analysis per machine p.a.</b>	
Value added	£309,810
M/C operator costs	£105,000
CMM operator costs	£78,750
Depreciation costs	£56,000
Scrap costs	£14,050
Concession costs	£7,025
Depreciation on deferred capital	£0
Margin per year	<b>£48,934</b>

So what happens to the process outcomes and margin when we implement each layer of the Pyramid? In all the examples below, it is assumed that any extra capacity is used to make more parts, deferring further capital spend.

### Process foundation

- Availability rises to 90% due to better machine reliability
- Performance rises by 5% due to fewer unplanned stoppages arising from input processes or environmental variations
- Quality rises by a quarter due to improved machine precision
- Manning levels are unchanged

### Process setting

- Availability remains at 90%
- Performance rises to 90% as set times are compressed and become more predictable
- Quality errors are halved compared to the previous layer as right first time rates rise thanks to automated, repeatable setting
- Manning levels at the machine are reduced as set times fall

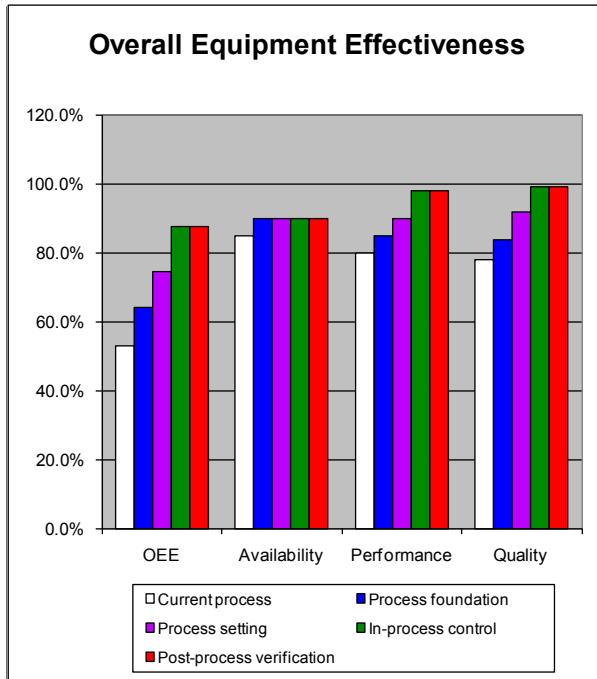
### In-process control

- Availability remains at 90%
- Performance rises to 98% as unplanned stoppages and time waiting for operators is reduced by automated in-cycle feedback
- Quality rises to 99% or higher as inherent variation is managed at source
- Manning levels are reduced as operator intervention is eliminated in a 'green button' process

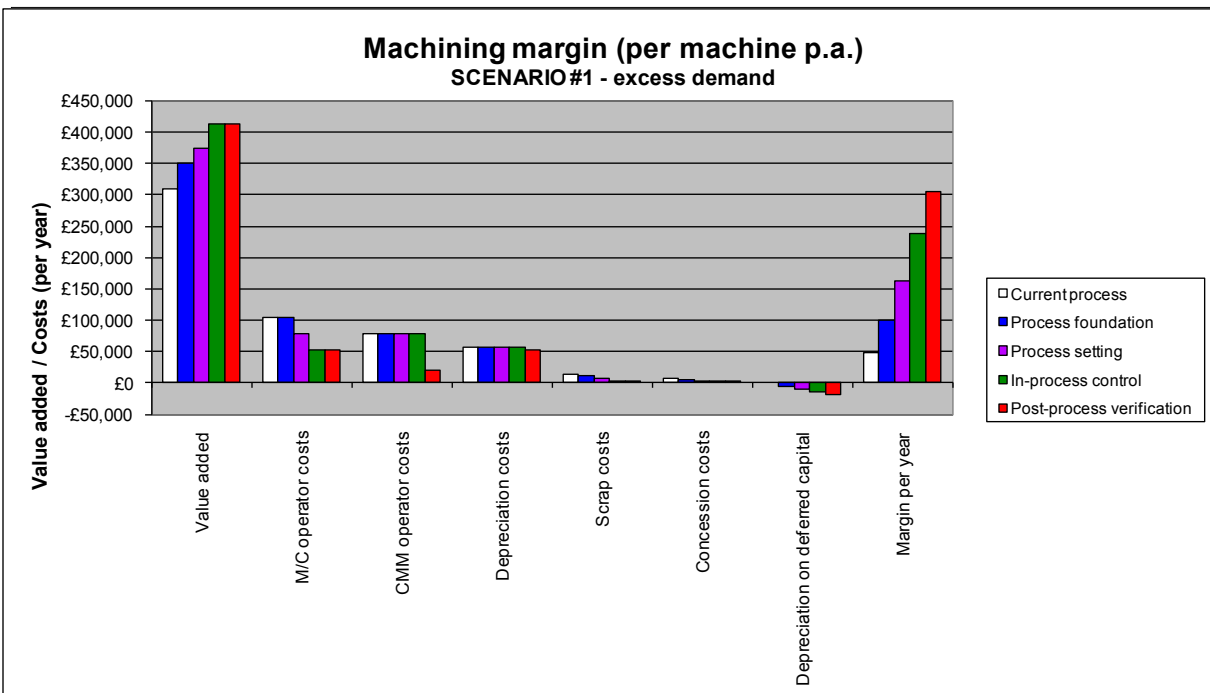
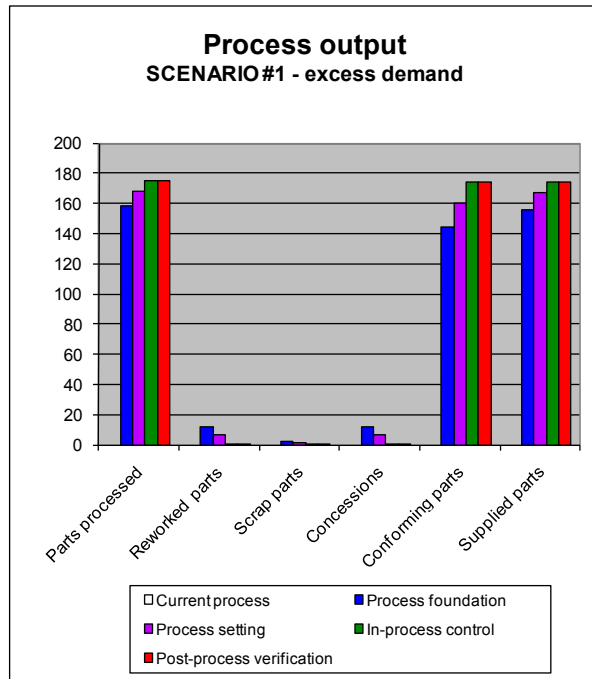
## Post-process monitoring

- Availability, performance and quality are unaffected
- The machine to CMM ratio rises as the CMMs become more productive with new sensor technology
- Manning levels on the CMM are reduced due to greater automation

This chart shows the trends in the elements of OEE that result from applying the four levels of controls:



This chart shows the number of parts processed, as well as levels of rework, scrap and concessions:



This chart summarises the value added, costs and margin that the machine generates in a year under different levels of process control.

The incremental improvement from full implementation of all four Pyramid layers is around £250k p.a. - equivalent to half the capital cost of the machine tool each year



## Summary and recommendations

The Productive Process Pyramid™ provides a systematic approach to eliminating variation in machining processes. Without making any fundamental changes to the machining process, improved process control can yield substantial recurring cost savings through greater automation and lower quality costs. The level of investment required to implement such controls is relatively low, with a payback of just a few months. Eliminating variation from your processes will also increase the returns on any future capital investments that you make.

The Pyramid controls should be implemented from the bottom up, as each layer builds on the one below to progressively reduce variation. Widely implementing the process foundation layer is an excellent first step, followed by implementing probing to automate setting processes. In-process control is more process-specific, and makes sense where there are many similar machines and processes to share the improvements across. If each machine in your facility is different, implementing this layer may prove time consuming. If this is the case, a better strategy will be to rationalise your machining platforms and implement these higher level controls on new processes so that any learning can be replicated on other new parts.

Replacing post-process measurement on your CMMs with on-machine measurement is generally not the best strategy. The machine's primary purpose is to make good parts, and so any verification that is done on the machine should be focussed on the process just completed rather than checking every feature on the part. On-machine verification makes most sense where parts are very large and complex, where a capable offline inspection process doesn't exist, or where the lead time and cost of moving parts is high. Attention must be paid to the accuracy of on-machine measurement, particularly the effects of temperature. In most circumstances, a CMM that employs high speed scanning technology is generally the most cost-effective way to verify component geometry and surface conformance. New versatile gauging offers a cost-effective shop floor inspection capability on medium- and high- volume parts.

**A tough business environment is placing extreme pressure on firms to address their productivity and costs. Applying the controls outlined in the Productive Process Pyramid™ is a cost-effective way to respond, placing your business in a strong position to compete internationally.**



*5-axis scanning technology is revolutionising CMM inspection*

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A worldwide network of subsidiary companies and distributors provides exceptional service and support for its customers.

### Products include:

- Dental CAD/CAM scanning and milling systems.
- Encoder systems for high accuracy linear, angle and rotary position feedback.
- Laser and ballbar systems for performance measurement and calibration of machines.
- Medical devices for neurosurgical applications.
- Probe systems and software for job set-up, tool setting and inspection on CNC machine tools.
- Raman spectroscopy systems for non-destructive material analysis.
- Sensor systems and software for measurement on CMMs (co-ordinate measuring machines).
- Stylus for CMM and machine tool probe applications.

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