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White paper

Evolution of the Renishaw Productivity System^{TM}

Precision, high quality manufacturing, closely coupled to its design operations, is a core element of Renishaw's business strategy. For over 15 years, the company has followed a concerted approach of design for manufacture, coupled with a relentless focus on eliminating or controlling sources of process variation in its machining operations. The results are predictable, automated, productive processes and faster new product introductions.

Introduction

Renishaw is a UK-based producer of precision metrology (dimensional measurement) equipment, which it sells mainly to manufacturing industry around the world. Throughout its 33-year history, the company has been a major exporter, with over 90% of its £175 million sales coming from outside the UK. The company's design, engineering and manufacturing facilities are based in Gloucestershire. The machine shop, recently moved to a 100,000 square foot facility at Stonehouse, faces a tough productivity challenge: to be cost-competitive compared to developing economies, whilst maintaining the benefits of its close ties to the design and engineering functions located locally. The shop produces a range of over 5,000 intricate components, made to aerospace tolerances and yet with automotive efficiency levels. With just 78 direct staff (over three shifts) supporting 70 CNC machines, Renishaw demonstrably continues to manufacture efficiently in the UK.

This white paper charts the journey that Renishaw has travelled as it scaled up its manufacturing operations – the challenges that it faced and the sound engineering methods that underpin the Renishaw Productivity System^{TM}.

Enough is enough!

Renishaw became a public company in 1983, when its annual turnover was just £3.4 million. Throughout the 1980s, its range of probing solutions for co-ordinate measuring machines (CMMs) and CNC machine tools were in increasingly strong demand and the company grew very quickly. By 1990, sales had reached over £47 million, a compound annual growth rate of nearly 40%.

This had put great pressure on its manufacturing operations, which struggled to keep pace with rampant demand. With plans to diversify into other areas of industrial metrology, continued growth was expected. Throughout the period, the company invested in the latest CNC machine tools, and by this time had 28 machines of various types, including 4- and 5-axis machining centres, multi-turret mill-turning centres, plus sliding-head and conventional lathes, located in two factories. The manufacturing engineering team had already made efforts to introduce greater automation, focussing on one-hit machining methods and a machining centre with a pallet pool. A multi-part fixturing system had recently been introduced on some of the mills, which showed great promise in terms of improved productivity. And of course, touch probes were used extensively to streamline batch changeovers and to provide in-process feedback.

Despite this, the company's management soon realised that massive further investment in plant and staff would be needed to cater for the anticipated future growth of the business. It also concluded that it was time for a change of approach. The main machining facility was located in a listed Victorian factory – complete with north lights and cast iron columns supporting the roof – and was by now full to bursting point (see Fig 1).

Fig 1 – machining centres in Renishaw's factory c. 1990

A new factory would soon be needed, and this provided an excellent opportunity to make improvements. Renishaw's Board was also becoming concerned with the lead times to get its increasingly complex new products to market, with the time taken to engineer new processes being a significant barrier.

A strategic shift

The company developed a new manufacturing strategy with the following goals:

- Scale up the machining capacity based on fewer, more flexible, more productive machining platforms.
- Remove human intervention from all stages of the process to reduce unit labour costs and improve quality.
- Bring critical processes in-house where feasible to control quality and costs.
- Reduce the lead time required to introduce new products by standardising the machining process and implementing concurrent engineering.
- Make as many parts as possible on a single work-centre to avoid queue and move lead times and work-in-progress.
- Focus effort on new products and allow market obsolescence to gradually eliminate the less efficient processes over time.

Reducing the variables

This strategy was underpinned by sound manufacturing engineering principles (see Box 1). The first step was to reduce the number of variables that the engineers had to deal with by rationalising the machines that would be used in the future. Renishaw identified just three machining platforms that it needed to make its future products and resolved to buy only these machine types in the future.

This was a fundamental shift away from the previous policy of buying the latest technology as it emerged, which had led to the company owning around a dozen different types of machine. A result of this original approach had been inflexibility – if a lone machine was down, then parts had to be re-programmed onto a different machine to keep production up and running, sucking in resources and adding to costs.

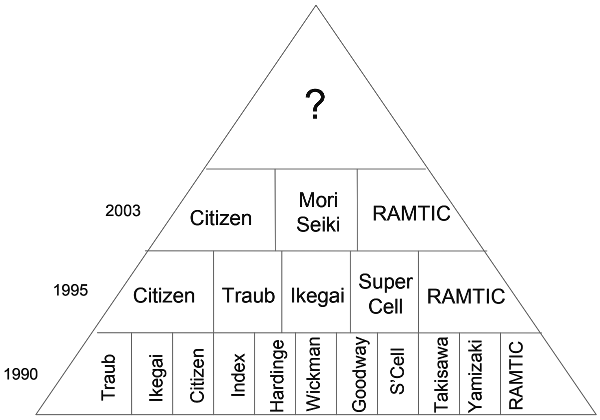


Fig 2 – progressive rationalisation of machining platforms

The machine rationalisation strategy, which was based on selection criteria of productivity and capacity for automation, took time to play out (see Fig 2). The chosen machining platforms were used for all new products, and so the workload through these ramped up over time as these new products found their place in the market. In some cases, these substituted existing products, and so the demand for throughput on the older machines steadily reduced, allowing them to be progressively phased out.

Another aspect of rationalisation was to reduce the range of processes and tooling that were to be used. If a new part was given to three Renishaw engineers at this time, they would likely choose different tooling and cutting methods based on past experience and preference. This was not a sustainable strategy going forward.

Renishaw's parts were analysed and broken down into standard features – slots, holes, threads etc – with which standard machining processes and tools could be associated. The next task was to select the best practice for each standard feature through process capability studies. Renishaw's engineers used Taguchi experiments to identify the optimum set of process parameters – tool choice, feed, speed, depth of cut etc. – for each feature / machining platform combination. This approach allowed for a limited period of experimentation, after which tooling and method choices could be made on the basis of hard data, rather than opinion.

BOX 1: principles underpinning Renishaw's strategy

- **RATIONALISE** processes, machines and tooling
- **SELECT** best practice through capability studies
- **AUTOMATE** through avoidance of non-controllable processes
- **STANDARDISE** on proven best practice
- **SIMPLIFY** routings by making core processes flexible
- **COMMUNICATE** best practice through guidebooks
- **IDENTIFY** sources of process non-conformance
- **PREVENT** non-conformance through process design (where possible)
- **MAINTAIN** equipment to prevent long-term performance reduction
- **CHECK** the health of performance-critical system elements
- **CATCH** human error through in-process checks
- **TRACK** inherent process variation and adapt the process
- **VERIFY** process performance and outcomes

Automation, automation, automation

A key consideration in the standardisation process was the capacity for automation. This meant avoiding ‘non-controllable’ processes, which were those that could not be adjusted in-cycle using tool wear offsets. Form tools (such as boring bars and reamers) were not preferred as their work could not be adjusted automatically – the size of the tool governed the size of the feature. As tool wear is an inevitable aspect of machining, it was important to be able to monitor it (using a probe) and adjust the process, without manual intervention. Wherever possible, Renishaw’s engineers selected processes that could be adjusted in this way – for instance, interpolating bores using slot drills.

The company was also keen to implement lean manufacturing principles, simplifying routings to eliminate non value-added activities. The core machining processes were designed to be sufficiently flexible to allow all the major components in a product to be made in one work-centre. In the case of Renishaw’s RAMTIC system (see box 2), this meant that typical parts underwent two milling operations on the same machine, and even finish turning could be performed without moving parts to another machine.

Making it happen

With the best methods and tooling identified, it was important to ensure that all engineers adopted the state-of-the-art methods. This required management leadership and enforcement at design reviews. Renishaw’s Chairman and Chief Executive, Sir David McMurtry, who is also the company’s leading designer, provided just this direction by piloting the new processes on a fast-track new product. He forced the design to be modified to make it easier to machine, taking the effort to design simplicity in and complexity out. The result was a development lead time of just nine months, two or three times faster than was typical at the time.

Fig 3 – Renishaw’s original DFM Guidebook, published in 1991

Renishaw chose to communicate the newly identified best practice through a DFM Guidebook (see Fig 3). The standard features, tooling and optimised processes were presented to product designers, initially in paper form. Against each feature type, a set of tools were listed and the capability that could be expected was defined (size & position tolerances, form and surface finish). The designers therefore knew what features could and could not be made and the tolerances that they should specify. The consequences of specifying tighter tolerances were also made plain as these would drive the use of non-preferred, higher cost processes.

The first guidebook was published after a few months of testing and was quickly put to use on new products. Thereafter, it was regularly refined and extended as further capability data became available. The guidebook is now available on the company’s intranet (see Fig 4) and the standard tooling and process parameters are embedded in the CAD/CAM system.

DIA	Holder	Insert TMS No.	Kitting D/Base
50.0	Shellmill		
63.0	Shellmill	E737	U-E737-MF1
80.0	Shellmill	E737	U-E737-MF2

Aluminium Capabilities

Diameter	Tolerance Face	Finish RA
50.0	0.05	0.4
63.0	0.05	0.4
80.0	0.05	0.4

Fig 4 – example standard feature definition, indicating the tooling to be used and the performance that can be expected

Renishaw made several other important changes to its design and engineering processes at this time, which together combined to change the culture of the company. A new Technology Centre was opened in 1991, which enabled designers and engineers to be co-located in multi-disciplinary project teams, fostering regular, informal communication. To reinforce the need for designers to know the manufacturing consequences of their design decisions, many of them spent time working as programmers.

A further change was the introduction of the UniGraphics CAD/CAM system, which improved communication within the project teams, based around solid models of the components and assemblies. It also provided CAM functionality to semi-automate part program generation, including integrated probing routines.

BOX 2: RAMTIC – Renishaw's flexible machining platform

Renishaw's Automated Milling Turning and Inspection Centre (RAMTIC) forms the backbone of the company's machining operations, producing most of the high-value components used in its products. Based around a standard vertical machining centre, the Renishaw-designed RAMTIC system includes a multi-part fixturing system, a movable pallet pool (or 'carousel') that docks next to the machine, and a transfer mechanism that moves pallets on and off the machine.

Fig 5 – RAMTIC systems in Renishaw's new machining facility at Stonehouse

The carousel comprises an indexable chain of 50 locations, each of which can hold a standard dovetail fixture, onto which can be mounted either parts or tools (see Fig 6). Each carousel is loaded with small batches (typically around 10) of each of a kit of parts, which together form the major components of a single product. The carousels are also stocked with the cutting tools needed to make the parts – typically less than 20 tools are needed as a result of process standardisation – and can run on any of the RAMTIC machines, allowing for flexible scheduling and short leadtimes through the shop.

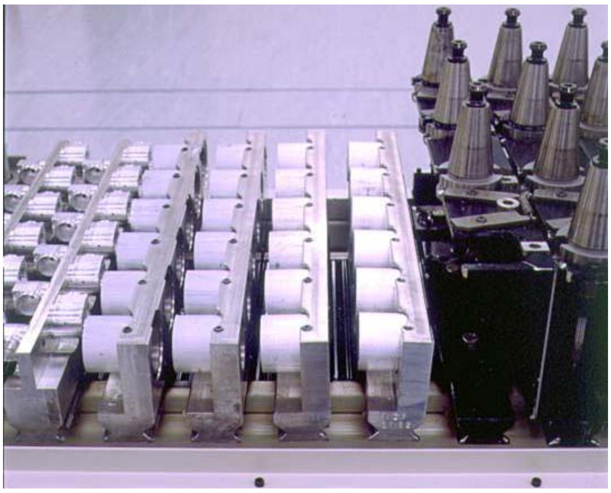


Fig 6 – pallets containing tools, billets and second operation parts on the RAMTIC 'carousel'

Fig 7 – measuring a calibrated 'artefact', which removes thermal and geometry errors from on-machine inspection

The machining process is highly automated, typically running for 24 hours without operator intervention. Once the carousel docks with the machine, the necessary part programs are pulled down from the DNC server and the process starts. Pallets are transferred to and fro between the machine and the carousel. Probes are used throughout the process to set tools, to check tool projections, to establish centre-lines of rotation, to track thermal drift, to check tool condition, to measure parts in-process and to update work and tool offsets during machining. A calibrated 'artefact' is stored in the machine and is probed periodically to eliminate the effects of thermal drift, growth and distortion from the on-machine measurements (see Fig 7). In some cases, final operation parts are mounted onto shanks so that they can be turned against fixed tools mounted on a special fixture.

Fig 8 – RAMTIC off-line kitting station

Once machining is complete, the carousel is moved to a kitting station (see Fig 8) where the finished parts are removed and replaced with fresh billets. Tool life is monitored and worn or damaged tools are replaced such that the carousel is ready to run again.

Stability is vital

The automated machining processes that run on Renishaw's machining centres and mill-turn machines depend heavily on a stable operating environment. Without such stability, sources of variation in the environment can impinge upon the process, causing it either to fail or to produce unexpected results. Most of the human effort in the factory goes into maintaining this stability, rather than running the processes themselves. Predictable productivity depends on such diligence.

With rationalised, standardised, automated process in place, Renishaw's engineers systematically analysed the possible remaining causes of process non-conformance. Using standard techniques like fishbone diagrams (see Fig 9) and process FMEAs, the engineers identified the factors that could adversely affect productivity and quality, and set about eliminating their effects.

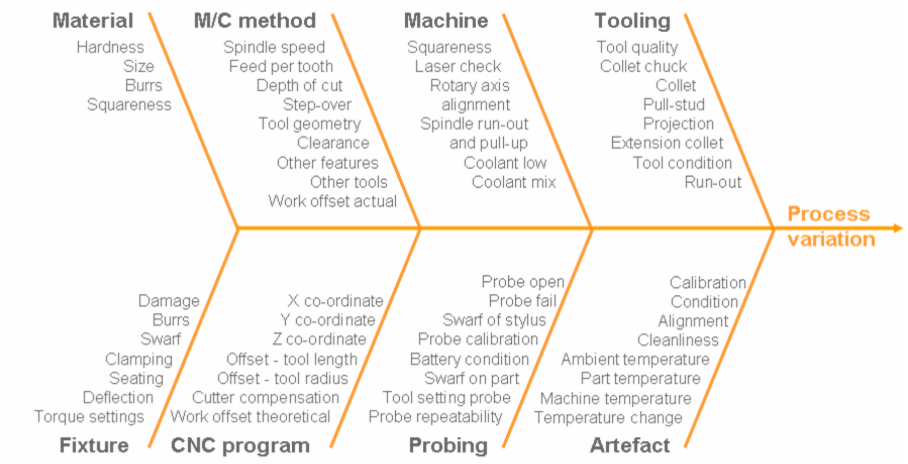


Fig 9 – 'fishbone' diagram showing the potential sources of non-conformance in an automated machining process

Designing non-conformance out

Where possible, non-conformance was prevented through process design: standards were enforced or in-process checks put in place. Some examples include:

- Torque wrenches with specified setting are used to clamp all billets into RAMTIC fixtures.
- Tool projections are specified and height gauges provided to assist with tool assembly. The automated in-process tool setting operation compares actual tool projections to the process standard and stops the process in the event of excessive deviation.
- All part programs are managed via a DNC system and cannot be modified, preventing shop-floor changes that might result in unplanned variation.
- Tool life is monitored and a conservative replacement strategy is enforced, so that the tools are kept in good condition and do not behave erratically.
- Renishaw grinds and regrinds its own carbide cutting tools so that it can control the geometry (as well as getting several times the operating life).
- Raw material preparation is highly automated, using CNC saws and deburring machines to ensure that billets sit flush in fixtures.

Maintain to sustain

Another important aspect of defect avoidance is preventative maintenance of performance-critical equipment. To maintain consistent part dimensions and geometries, it is vital that all elements of the system that affect part accuracy are kept in good condition.

Renishaw's machines themselves undergo rigorous maintenance schedules, including spindle vibration checks and lubricant / coolant changes. Other system elements such as the 'artefact' are regularly checked for condition and periodically re-calibrated on a CMM. Finally, the on-machine probing systems are also regularly refurbished / replaced as required.

A key task for the machine operators is to ensure that the machining system is kept in good working order. 'Pre-flight checklists' are used to ensure that appropriate checks and day-to-day maintenance tasks are completed before a day's production can begin:

- Machine warm-up cycles are run to ensure that the system is thermally stable before cutting parts.
- Swarf is cleared and coolant nozzles are checked for blockages and alignment.
- The spindle taper is checked for cleanliness and the tool changer for obstructions.
- The feed-rate and rapid override switches must be set to 100% to ensure that programs run at the correct speed.
- Key control variables in the CNC must be correctly set.

The checklists must be signed by operators and are checked by shift supervisors.

Precision comes from control

In addition to the long-term strategy of design for manufacture and the shop-floor disciplines needed to maintain a stable operating environment, process control is the final piece of the predictable productivity jigsaw. There are still many sources of variation that occur day-to-day, hour-to-hour and even minute-to-minute that must be managed by the automated process itself.

The Productive Process Pyramid™ (see Fig 10) summarises the layers of process control that build upon one another to yield consistent process performance. Between them, these controls:

- check the health of performance-critical elements of the system,
- catch human error in preceding processes by implementing in-process probing checks,
- track inherent process variation, using offsets to adapt the process to suit,
- verify the process performance and outcomes.

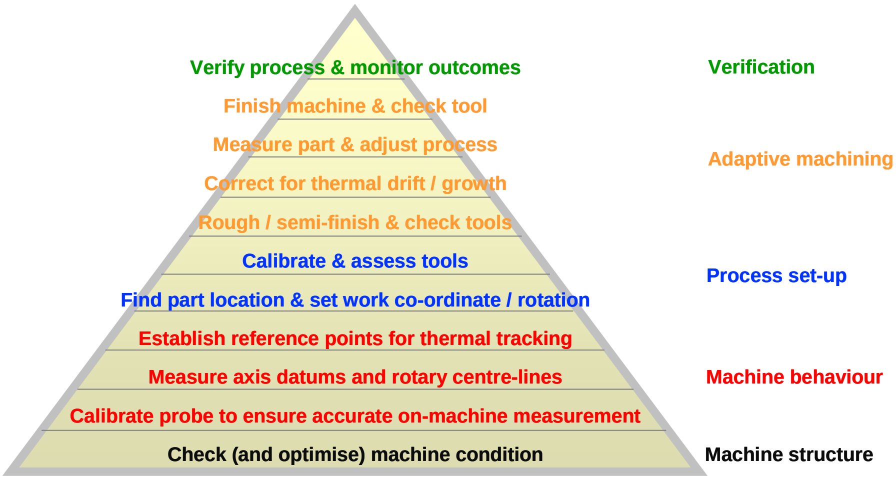


Fig 10 – the Productive Process Pyramid™, illustrating the layers of control needed to consistently produce accurate machined components

The base layer of the Pyramid (coloured black) focuses on the precision of the machine structure. Each machine is subject to regular laser calibration (see Fig 11), which compensates for minor errors in axis linearity and backlash, improving the precision with which the machine can move. These are supplemented by more frequent ballbar checks, which monitor the machine's ability to follow a circular contour and hold a true position. This provides a performance benchmark which is tracked to highlight any deterioration in performance.

Fig 11 – calibrating a turning centre with a laser interferometer

Updating set-up offsets

The next controls (red) focus on the key geometric relationships on the machine, and use a touch probe to monitor how the machine behaves. The probe is calibrated to ensure that the position and size of the stylus ball is known precisely. The probe can then be used to establish datums on the machine, such as the centre-lines of rotary axes. Knowledge about the location of these points is critical since they govern how the parts and tools move during the machining process.

Temperature is a major factor in machine behaviour. Whilst Renishaw controls both the ambient temperature of its machine shop (to within ±2 °C) and the coolant on its machines, heat is still generated during the process and this can affect both the part and the machine's structure. Tracking and eliminating the impact of temperature on the machine is simply done by re-establishing the location of key datum points (e.g. a rotary axis centre-line) and updating a work co-ordinate. These checks are performed on Renishaw's RAMTIC system before machining each new pallet.

With knowledge of how the machine is behaving, the next controls (blue) focus on process set-up – establishing the location of the parts to be machined and the dimensions of the tools that will cut them. In the case of first operation parts, it is only necessary to find the position of the pallet roughly, whereas second operation and turned parts may need more accurate set-up on an individual basis to ensure that machining is correct with respect to previous operations. The tool setting process includes checks against tool assembly build standards to ensure that the manual kitting process has been performed correctly.

Adapting to changing circumstances

Once machining starts, Renishaw's automated processes use an adaptive machining strategy (orange) to ensure consistently good results. Even with all the lower level controls in place, machining processes are still subject to variation due to temperature change, heat flows and tool wear, as well as the inherent repeatability of the machining process. The effects of temperature and tool wear will, if left uncorrected over time, lead to unacceptable process drift, and so these must be controlled.

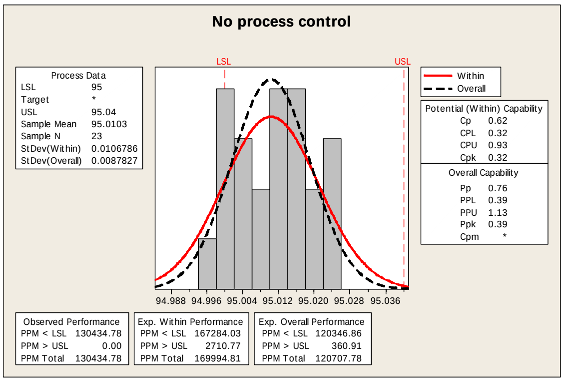
Adaptive machining involves applying control to each of the tools that combine to produce the finished part – not just the finishing tools. The first step is to complete all roughing processes. This puts significant heat into the system, so it is sensible to get this out of the way before moving onto the critical finishing cuts. Coolant washes are used to bring the part back to a normal temperature. Before each tool is replaced in the tool magazine, it is checked for damage. One 'control' feature is then measured for each roughing tool and its tool wear offset is updated.

The next stage is to finish the part. On some processes where a significant level of part-to-part variation is observed, a semi-finishing strategy is used. This requires the roughing process to leave sufficient material on the part for two finishing cuts. The first (semi-finishing) cut removes half of this material. A control feature on the part is then checked with the touch probe and the tool wear offset is adjusted to bring the finishing cut back on target. Once the finishing cut is complete, the final surface can be checked to verify the process outcome. See Box 3 for an example of the impact of adaptive machining on process capability.

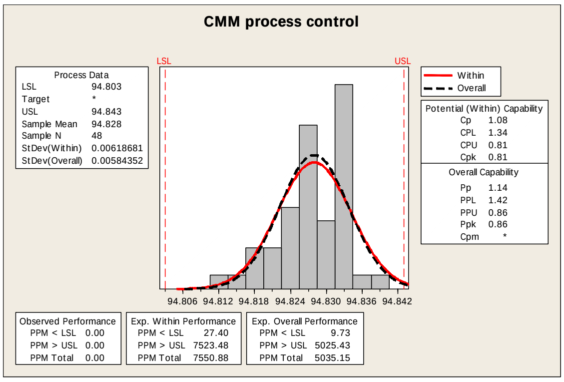
On the RAMTIC system, where process stability is high, Renishaw uses a sample verification process (green). The first part is used to set the process, with each tool wear offset being updated. Thereafter, the rest of the batch is machined without any measurement or process updates. Batches are typically small (10 to 20 components) and tool wear within a batch is generally not critical when compared to the tolerances that must be achieved. The last part is inspected fully and, if correct, the whole batch is assumed to be in specification. This assumption can be made on the back of the huge amount of process capability data that has been gathered over the years.

BOX 3: adaptive machining in action

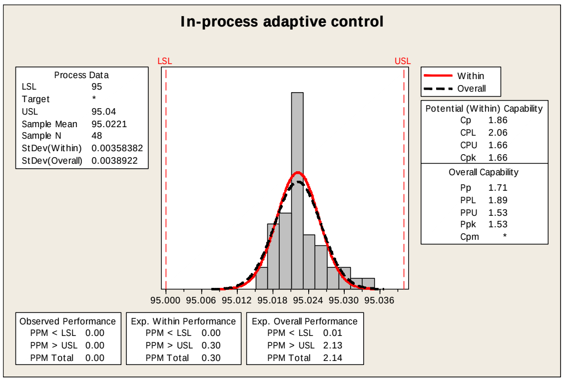
Renishaw's angle encoders comprise a steel ring with a precision-turned internal bore and taper. When run with no process control, the process shows unacceptable variation (C_{pk} = 0.32, scrap = 12.1%):



When the finished part is inspected, and the results used to update the finish tool offset on the next part, things improve somewhat (C_{pk} = 0.81). The process is now compensating for tool wear:



With a semi-finishing cut, an in-process measurement and adaptive machining using a 75% error feedback regime, the capability improves markedly (C_{pk} = 1.66):



Where part-to-part variation is caused by upstream processes, the size of one part is not a good predictor for the next, and adaptive machining is the best strategy.

The temperature challenge

In Renishaw's original machine shop, the ambient temperature was not controlled and the machines were subjected to substantial changes in the thermal environment. In winter, it was cold and shop floor heaters were needed to keep the operators warm, whereas summer temperatures could be sweltering. During a typical 24-hour period, the temperature could vary by as much as 20 ºC between night and day. When the door was opened to the (external) raw material store, air would flood in, adversely affecting the neighbouring machines.

Self-generated heat was also a factor. As machines do their work they generate heat in their electric motors, in their ball-screws and slide-ways, in the cutting tools, in the chips and in the part itself. Heat flows – from ambient temperature changes or internal heat sources – affect the machine's structure and the component, causing them to grow and distort, and can easily consume all of the available tolerance (see Box 4).

In the early days, Renishaw's machines did not feature temperature controlled coolant and thermal compensation as they do now, and so thermally-induced process variation was a significant obstacle to automation. This, combined with a desire to eliminate offline (and labour-intensive) post-process verification, led Renishaw to develop its patented artefact comparison technique.

An 'artefact' is a workpiece that resides in the machine, with dimensions that have been calibrated on a CMM under controlled thermal conditions (usually at 20 ºC). The artefact is probed on the machine and its size is compared with the calibrated dimension. The error in the measured size is a result of minor inaccuracies in the machine's structure, thermal distortions of the machine, or growth of the artefact. This error can be used to derive a scaling factor to correct other measurements made on the machine, reducing the measurement uncertainty (see Box 5).

Since 1995, Renishaw's machine shop has featured ambient temperature control, and the latest generation of RAMTIC machines have thermal control and compensation. This has reduced the level of temperature variation, and hence the thermal growth and distortion, to the point where thermal growth is not a significant contributor to part-to-part variation in many cases. However, the traceable measurement capability provided by artefacts has enabled Renishaw to use on-machine verification, eliminating costly post-process inspection processes.

BOX 4: when is temperature significant?

Metal components expand and contract with temperature, increasing the uncertainty of on-machine measurements. This table illustrates the proportion of a tolerance in a **steel** part (α = 11 ppm/ºC) consumed by a **±5 ºC** temperature uncertainty:

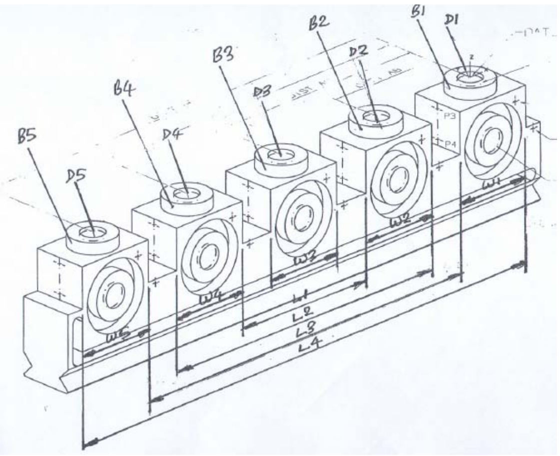
Feature size	**Tolerance** ±5μm	 ±25μm	 ±50μm	 ±100μm
10 mm	11%	2%	1%	1%
25 mm	28%	6%	3%	1%
50 mm	55%	11%	6%	3%
100 mm	110%	22%	11%	6%
250 mm	275%	55%	28%	14%
500 mm	550%	110%	55%	28%
1000 mm	1100%	220%	110%	55%
2500 mm	2750%	550%	275%	138%
5000 mm	5500%	1100%	550%	275%

How to deal with thermal uncertainty

0% - 10%	Insignificant – artefact not required
11% - 30%	Significant – consider artefact
> 30%	Dominant – artefact essential

BOX 5: how artefacts reduce measurement uncertainty

Renishaw uses a generic artefact on its RAMTIC machines, comprising a series of webs, bores and bosses. The artefact is calibrated on an accurate CMM at 20 ºC.



In a test, a series features were measured on the machine tool, and errors in the longest dimension (L4) were used to derive a scaling factor to correct the other measurements, which were then compared with the calibrated values. The average measurement uncertainty (mean difference + 2σ) was **1.9 μm**, with a worst case error of 6.5 μm.

Important enablers

Despite early successes, Renishaw soon found that developing robust processes required the right environment. Throughout the early 1990s and even after moving into a new machining facility at New Mills in 1995, the engineers were developing new processes on machines that were also required for production. The meant that process development had to halt each night to allow production to run overnight. Too often the results were under-developed processes being handed over to production, resulting in ongoing shop support and poor productivity.

With the company increasingly anxious to reduce new product development leadtimes, and the quality requirements of customers rising inexorably, Renishaw's management chose to invest in dedicated development machines to allow process prove-out, capability studies and new tooling testing to proceed smoothly. Due to pressure on space, however, these machines had to be tucked away in different parts of the site. Following the recent move of the machine shop to the larger facility at Stonehouse, the previous machine hall at New Mills has been converted into a £ multi-million dedicated development area. This provides for new machining process development (see Fig 12), as well as for surface mount electronics (Fig 13) and mechanical assembly development.

The manufacturing engineers have access to each of the three machine classes and can prove out new parts, based on standard processes and tooling suites. In addition, some engineers are focussed on developing new process technologies – e.g. introducing probing onto new machine classes or testing out improved versions of proven machining platforms. Once proven here, these technologies will be rolled out into production and the DFM guidelines updated accordingly.

Fig 12 – machining process development facility, New Mills

Fig 13 – surface mount electronics development facility, New Mills

Multi-functional engineers

Over the last 15 years, the role of the manufacturing engineer at Renishaw has changed as standardised processes have become the norm. Rather than deskilling the activity, if anything the demands are greater than ever. Engineers are expected to manage a project 'from cradle to grave', without resorting to skilled specialists to do particular tasks.

Engineers are expected to:

- manage all DFM liaison with the project team, getting involved early in the design process
- calculation and optimisation of component costs
- design, program and manufacture all fixturing (on the production machines)
- generate CNC programs for all components in the product
- select tooling
- prove-out all processes
- manufacture pre-production batches and establish process capability
- document processes
- handover to production

In with the new

Another by-product of the move towards DFM is a reduction in the demand for shop support. With the machining processes having bedded down over many years, the majority of engineers (around 70%) are focussed entirely on new product development, with just 30% supporting current processes. Previously, this ratio was reversed.

Business benefits

This table highlights the impact that Renishaw's manufacturing strategy has had upon its productivity:

	1991	2006	Change
Sales	£47.6 M	£175.8 M	+285%
Machine shop data			
CNC machines	28	70	+150%
Machine types	11	3	-73%
Direct staff	55	78	+42%
Parts / month	50,000	300,000	+500%
Productivity ratios			
Sales / m/c p.a.	£1.63 M	£2.51 M	+54%
Parts / m/c p.a.	21,429	51,429	+140%
Sales / direct staff	£0.83 M	£2.25 M	+171%
Man-hours / part	0.16	0.04	-76%
Engineering data			
MEs new products	5	22	+340%
MEs shop support	9	11	+22%

What it means for the people

- **Operators** now support automated processes, rather than intervene in them.
- **Engineers** focus on introducing new products using known processes, rather than 'having a go' at making parts with impossible tolerances.
- **Designers** are aware of production capabilities and design within them in all but exceptional circumstances.
- **Management** focuses on eliminating increasingly detailed causes of process failure in existing processes, whilst seeking out new technologies to make further step changes in productivity.
- **Customers** receive high quality parts in a timely manner.

BOX 6: manufacturing transformation timeline

1990	- Decision to rationalise machining processes. - Design of prototype RAMTIC system.
1991	- Process capability studies & tests to select optimum tooling & method for milling aluminium. - First (paper) edition of DFM Guidebook issued. - Artefact comparison process developed, enabling traceable on-machine measurement. - RAMTIC automation design refined and kitting station concept developed. - Group Technology Centre opened.
1992	- DFM Guidebook applied to first product (MIP). - First RAMTIC production trials (3 machines).
1993	- Inspection probing integrated into UniGraphics CAD/CAM system, allowing auto program generation from gauge points on solid model. - 4 RAMTIC machines in production
1995	- Machining moved to new facility at New Mills. - Machine classes rationalised from 11 to 5, with limited re-engineering to permit obsolescence of older platforms. - 7 RAMTIC machines in production.
1996	- Development RAMTIC machine allocated to Engineering.
1997	- 'Pre-flight checks' on RAMTIC systems.
1999	- First high-speed version of RAMTIC trialled. - 11 RAMTIC machines in production.
2001	- Mori Seiki mill-turn machines selected as Renishaw's large-part mill-turn platform. - 19 RAMTIC machines in production.
2004	- Renishaw acquires Stonehouse facility and sets about refurbishing it ready for occupancy.
2005	- Full automation of Mori Seiki machines using innovative probing processes.
2006	- Machines moved from New Mills to Stonehouse, with additional capacity added. - Consolidated 'development facility' at New Mills. - Billet preparation facilities improved. - 28 RAMTIC machines in production.

Fig 14 – sliding-head lathes in Renishaw's Stonehouse facility

Renishaw Productivity System™ in summary

Renishaw has built its current impressive manufacturing productivity on a series of sound engineering principles. The first and most vital decision was to pursue a design for manufacture strategy, which narrowed the field of endeavour down to something manageable. Without this, the company's engineers would still be running capability trials to understand a vast range of different processes.

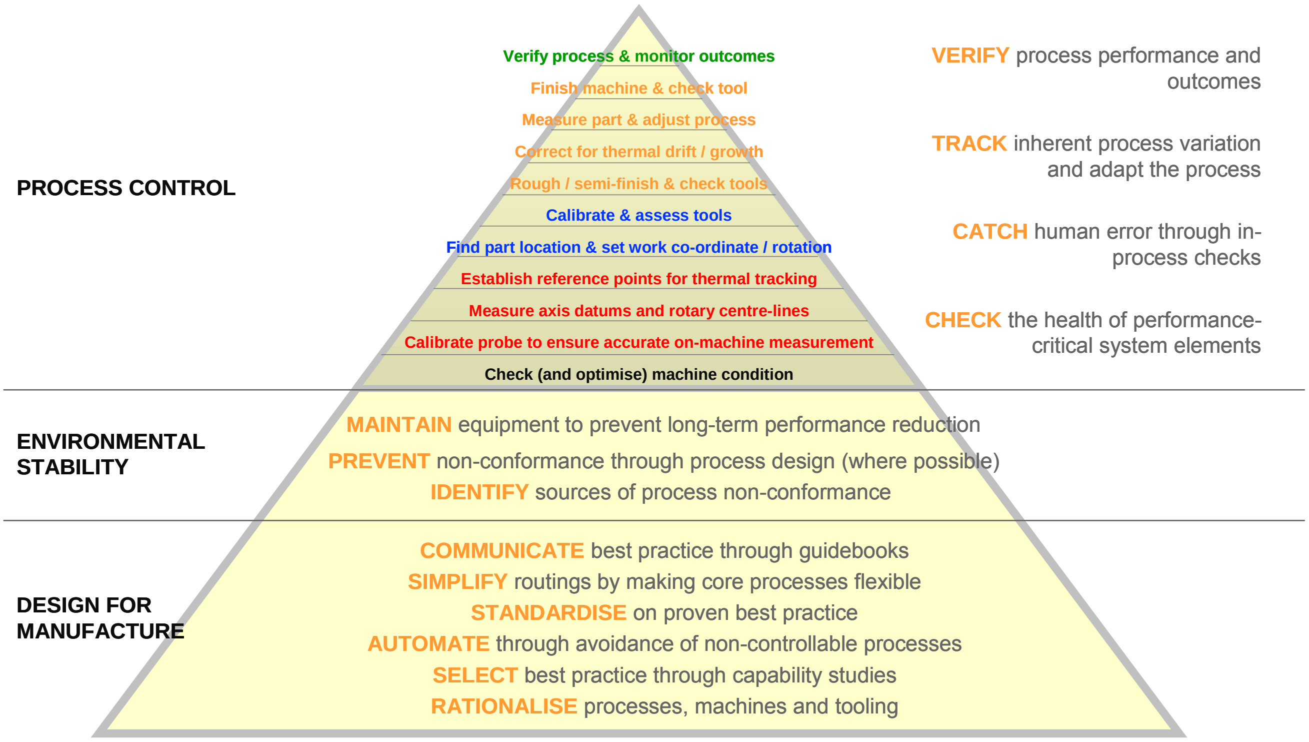


Fig 15 – Renishaw Productivity System™ in summary - the Productive Process Pyramid™, underpinned by design for manufacture and environmental stability

When faced with a broad range of processes, many of which were under-performing, it was important to take pragmatic decisions about what to improve and what to leave alone. Renishaw chose to engineer new products onto the new processes, rather than go back and address existing parts. This drove a wedge of new techniques into the shop, which gradually squeezed out obsolete process and machines.

It was also vital not to let the perfect be the enemy of the good – making some standardisation choices without complete information, then refining them later as more data became available. Standardisation itself is valuable, providing a clear benchmark from which improvement initiatives can then be launched.

As Renishaw has modernised its machining facilities, it has paid increasing attention to the working environment – both for the machines and for the workforce. Successful automation happens best in a clean, stable environment, where machines, fixtures and tools are all well-maintained, and where staff adopt clearly-defined disciplines.

Of course, new machine tools and the application of Renishaw's own probes and calibration technologies are central to Renishaw's manufacturing productivity. By paying close attention to the condition of its machines, and by using in-process measurements and feedback to provide automated control, this has enabled reduced manning and more output per direct worker.

It has been a 15-year journey, and one that will never really be finished. International competition is driving Renishaw to seek further improvements – both incremental and step-change – to keep man-hours per part on a downward trend. The company is extending probing to its sliding-head lathes and investigating future machining platforms to further increase automation, to reduce cycle times and to enhance quality.

Predictability might sound a little boring – where's the challenge of 'on the hoof' problem solving or the pressure of fire fighting? The excitement of running processes on a knife edge is the kind of thrill Renishaw can live without! It prefers to focus on the bigger picture – continuing to manufacture profitably in the UK.

The results

Fig 16 – RAMTIC machines in Renishaw's machining facility at Stonehouse, Gloucestershire, UK

Comments in the press

"It is still a surprise to enter a machine shop that is so clean, quiet, bright and minimally populated with people unhurriedly focussed on supporting and maintaining capable processes that run automatically." ***Machinery, Dec 2006***

"In the struggle to convince youngsters that engineering is not a grimy, spanner-in-hand profession, those entrusted with improving the industry's image could do worse than persuade Renishaw to open the gates of its new factory to all and sundry." ***Professional Engineering, Nov 2006***

"Common sense was the inspiration behind Renishaw's new Stonehouse machining facility, which astonishes the visitor with a simplicity and pragmatism still rare among western manufacturers." ***MWP Best Practice in UK Manufacturing, Jan 07***

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