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Practical Environmental Advice for Business

GG224

Preventing waste in production: practical methods for process control

Preventing waste in production: practical methods for process control

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Summary

This Good Practice Guide examines various tools and techniques that a company can apply to its production processes in order to save money, improve productivity and product quality, and reduce its environmental impact.

The Guide makes extensive use of a fictional example to demonstrate how these tools and techniques can:

- help to achieve control and minimise levels of waste;
- be introduced in a way that encourages their acceptance by staff.

It uses a structured approach that allows a company to:

- assess the cost of its waste, either using existing company records or by generating appropriate data;
- identify the points in a process where waste is arising, assess the specific costs in each case and present the findings in a format that will encourage action;
- construct and use simple diagrams to prioritise those process components that are most in need of attention and, perhaps, change;
- identify the possible causes of waste, using tools and techniques such as brainstorming, tally sheets, scattergrams, process maps and cause and effect diagrams;
- carry out a capability study that provides a numerical assessment of how consistent a process is and how well it is meeting the company's target specifications;
- identify actions that will improve the process and its capability;
- use control charts to maintain control once a process is operating satisfactorily.

The Guide, which describes the tools and techniques required and illustrates their application in a manufacturing situation, can be regarded as a blueprint for any company wishing to understand its own processes more fully and minimise process waste. It should be read in conjunction with Good Practice Guide (GG223) *Preventing Waste in Production: Industry Examples*, which is available through the Environment and Energy Helpline on 0800 585794.

Contents

Introduction

1.1 How this Guide will help you

This Guide and accompanying Good Practice Guide (GG223) *Preventing Waste in Production: Industry Examples*[1], introduce a range of tools and techniques that use process data to identify and prevent waste in production processes. Companies that have tackled production waste in this way have achieved cost savings of up to 1% of turnover.

These savings result from minimising:

- the excessive consumption of energy or raw materials;
- losses in the process itself (lost yield and sales);
- any problems arising when the product is used in a subsequent manufacturing step (reduced yield and possible 'bottleneck' difficulties);
- rejects at the inspection stage;
- in-service failures.

Although the tools and techniques described in the Guides are based on tried and tested statistical techniques, they are straightforward to use and do not require specialist statistical knowledge.

By adopting a similar approach and applying the relevant tools and techniques to its production processes, your company can achieve:

- cost savings;
- higher productivity;
- higher product quality;
- a lower environmental impact.

This Guide examines a range of tools and techniques that include simple aids for brainstorming and identifying priorities, and the construction of charts based on statistical principles. It uses a fictitious manufacturer (Green and Keen) to show how a company can use these approaches to achieve greater control over its production processes, and minimise waste.

By addressing one or more of the seven stages identified in the Guide (see Fig 1 overleaf) and making use of the relevant tools and techniques available, your company can:

- acquire a better understanding of its processes;
- analyse process performance and identify areas of avoidable waste;
- identify opportunities for process improvements;
- check that any improvements implemented have been effective;
- ensure that the level of improvement achieved has been maintained.

Furthermore, by reading this Guide alongside GG223, you will be able to see how real companies (see Table 1 overleaf) have benefited from this approach.

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[1] GG223 is available free of charge through the Environment and Energy Helpline on freephone 0800 585794.

Fig 1 A systematic approach to process improvement

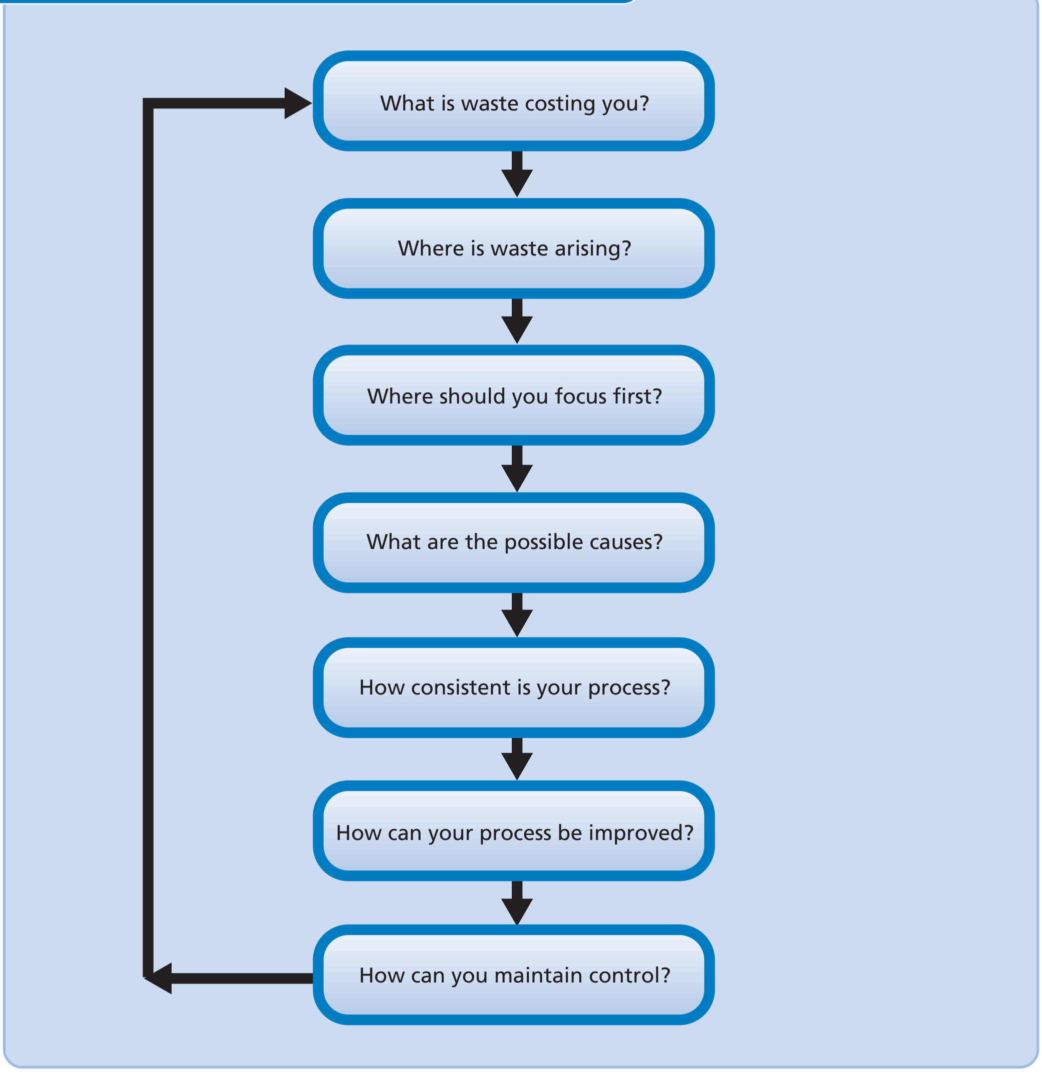


Table 1 Techniques employed by the Industry Example companies to achieve their aims (see GG223)

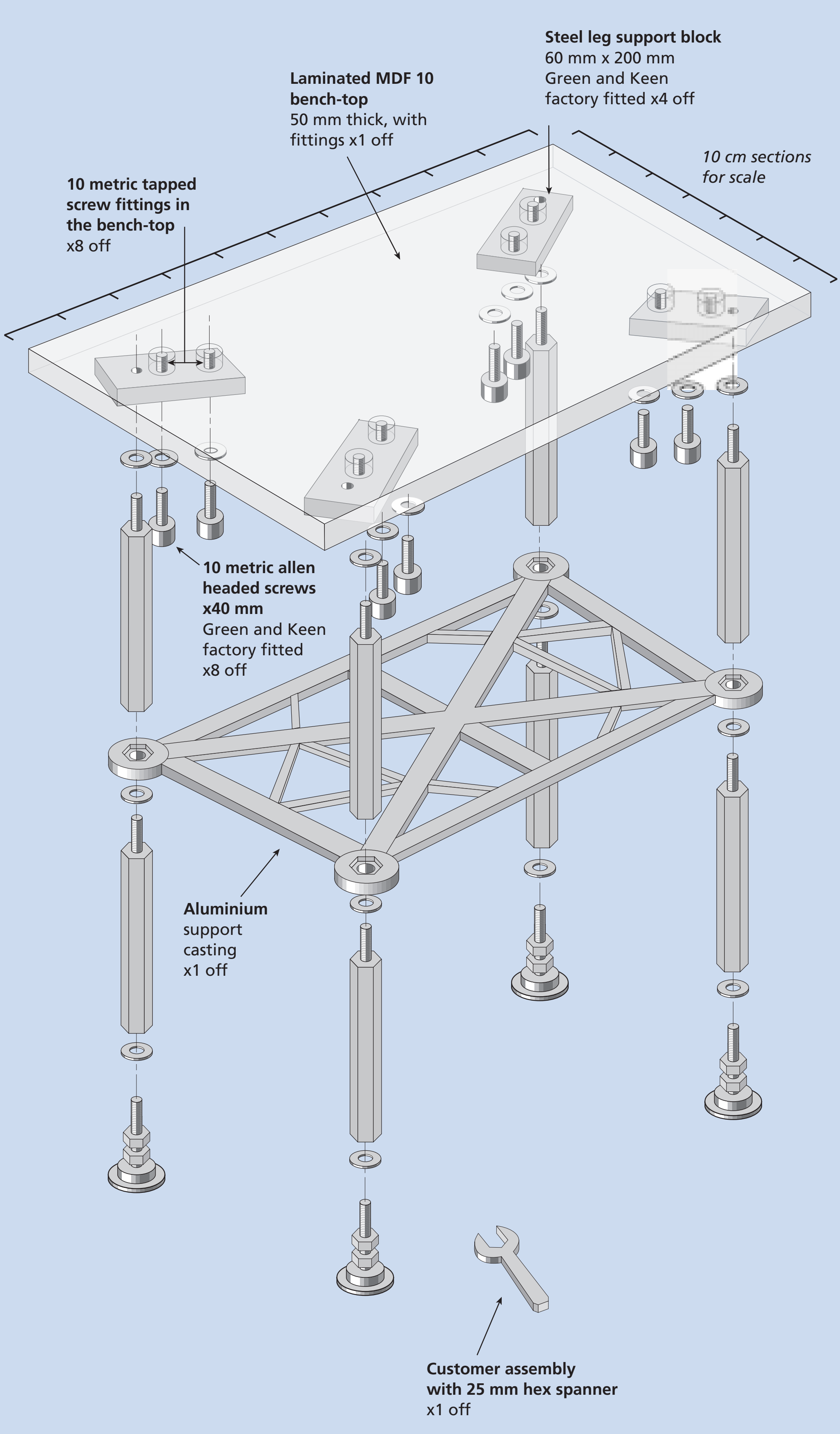
	Perstorp Ltd Furniture manufacture 1	C Shippam Ltd Food pastes/filling 2	Transprints Ltd Printing textiles transfer paper 3	Edinburgh Crystal Glassware manufacture 4	Novem Car interior (wooden veneers) 5	Illbruck Koike General rubber goods 6	Mitex GlassFibre Ltd Woven glassfibre 7	BFF Nonwovens Non-woven specialist fabrics 8	Fenner Conveyor Belting Composite conveyor belts 9	Corus Foundry Iron casting 10
What is waste costing you?										
Basic production data collection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Where is waste arising?										
Process mapping/flow chart				✓						
Where should you focus first?										
Histograms	✓		✓			✓	✓			
Pareto diagrams	✓			✓	✓					
What are the possible causes?										
'Fishbone' diagrams			✓							
Experiments/investigations	✓		✓		✓				✓	✓
How consistent is your process?										
Normal variability		✓								
Special variability						✓				
Capability assessment		✓								
How can your process be improved?										
Rechecking capability		✓								
How can you maintain control?										
Control charts					✓			✓		
Other										
Operator training			✓	✓				✓		
Automatic mixer control										✓

1.2 Introducing Green and Keen

Green and Keen manufactures a relatively heavy-duty, flat-pack, self-assembly workbench (see Fig 2 overleaf). It buys the basic bench-tops, which incorporate tapped fittings for the leg supports. In-house manufacturing operations consist of laminating these bench-tops and producing machined leg supports that are assembled into each bench-top.

The company employs 22 staff and has an annual turnover of about £990 000, based on the production and sale of 11 000 workbenches at £89.99 each.

Fig 2 The Green and Keen workbench: an exploded diagram



What is waste costing you?

Section 2 uses the Green and Keen Industry Example to demonstrate how a company can assess the cost of its waste. Particular points highlighted include:

- the use of existing data to highlight a waste problem;
- the generation of additional data, where appropriate;
- selection of a suitable approach to waste cost assessment.

2.1 Identifying the problem

The waste problem at Green and Keen came to light in an accountant's report to the Managing Director. This showed that:

- the cost of replacing products following customer complaints had exceeded the replacement budget over a six-month period;
- the stock of bench-tops was reducing despite buying in more than were being sold - this was believed to be due to scrap.

A six-monthly summary of weekly customer complaints already existed (Table 2). This showed the number of workbenches for which credit notes had been raised, and the reasons.

Table 2 Weekly summary of customer complaints

W/E	No of complaints	Complaints details
03 Jul	7	Unable to fit legs into bench-top 5, poor adhesion 2
10 Jul	0	
17 Jul	13	Unable to fit legs into bench-top 4, bubbles in laminated surface 9
24 Jul	15	Colour 1, bubbles in laminated surface 12, damage 2
27 Nov	18	Unable to fit legs into bench-top 2, bubbles in laminated surface 5, legs fit too loosely into bench-top 4, poor adhesion 7
04 Dec	0	
Total	**218**	

No data were available on scrap levels, so operators were asked to keep scrap records for a two-week period (see Table 3 overleaf).

Table 3 Production rejects at the assembly stage over a two-week period

Week ending	Produced	Details of rejects	Total
6 Nov	239	Leg support failed 9, reworked 3	12
13 Nov	238	Leg support failed 9, reworked 5	14
Total	**477**		**26**

Table 3 shows that about 5% of bench-tops were lost or reworked at the leg support fitting stage. Further analysis showed that about 50% of these items had to be scrapped.

2.2 Assessing the costs of waste

The existence of a rejects problem does not necessarily mean that the problem is serious. Furthermore, a company may not find it economically viable to resolve a relatively minor problem of this type. The first task for Green and Keen was, therefore, to assess the cost of the complaints outlined in Table 2.

There are two possible approaches to the cost of replacing benches following complaints:

- If there is no evidence of business being lost because of complaints, and if the company is working below capacity, the cost of a complaint is limited to the cost of manufacturing the replacement and shipping it to the customer.
- If sales exceed production capacity, replacement items have to be produced in time that could have been spent manufacturing items for sale. The cost of a complaint is then the full sales value of the item.

Green and Keen adopted the first approach, ie a £56 manufacturing cost (assuming no components of a returned item could be salvaged for re-use) + a £10 transport cost for every workbench replaced.

The cost of the replacements was calculated for each type of complaint for the six-month period summarised in Table 2 (see Table 4). The total amounted to £14 388, equivalent to an annual cost of nearly £29 000.

In addition, there were two components to the cost of rejects generated during production at Green and Keen:

- a time and components cost of almost £10 000/year;
- the cost of paying a contractor to remove the waste components from site (25 skips at £180/skip = £4 500/year).

This gave an overall cost for production rejects of about £14 500/year.

Overall, customer complaints and production rejects were costing Green and Keen an estimated £43 500 - just under 4.5% of turnover.

A target was set to reduce this loss by at least half.

Table 4 The cost of customer complaints over a six-month period

Complaint	Number	Value	Transport	Cost (£)
Surface colour	10	56	10	660
Surface adhesion	34	56	10	2 244
Surface bubbles	76	56	10	5 016
Surface damage	12	56	10	792
Unable to fit legs into bench-top	22	56	10	1 452
Legs fit too loosely into bench-top	48	56	10	3 168
Other	16	56	10	1 056
Total	**218**			**14 388**

Study the Industry Examples in GG223 to see how individual companies have used existing production data to identify problems and assess their cost.

Where is waste arising?

Section 3 shows how you can identify the point in your process where waste is arising. This Section will demonstrate:

- the need for a common understanding of the process as a basis for identifying the main sources of waste;
- the value of involving accounts staff when assigning costs to the various components of the process;
- how you can present the findings in a suitable format, eg flow chart and table.

3.1 Establishing a common understanding of the process

To establish where waste is arising in a process it is necessary to have an accurate and agreed understanding of that process. One way of achieving this is to ask a member of staff - possibly the Production Director - to produce a rough flow chart of the process and to discuss its content with other relevant staff such as process operators and accounts staff. The regular production meeting may be an appropriate time for a 'brainstorming' or discussion session to ensure agreement.

When this approach was adopted at Green and Keen it became evident that different staff viewed the production process from a slightly different perspective. There were no basic technical disagreements, but there were differences in emphasis. Those attending the production meeting paid a visit to the production area, after which agreement was quickly reached on the key processes (eg cutting and drilling metal, assembling components) and on the order of production. The findings were noted on a flip-chart.

3.2 Identifying where waste is occurring

The next step is to identify those parts of the process where waste is occurring. Initially, a broad-brush approach is more appropriate than a detailed analysis. That can come later (see Section 5).

At Green and Keen, the production meeting demonstrated that there was no shortage of ideas but that operators had strong (and conflicting) opinions about which parts of the process were to blame for the rejects. By insisting on a broad-brush approach, the Production Director was able to obtain an initial 'feel' for how often lost time, and reject and assembly problems occurred at key stages in the process. This was noted on the flip-chart.

3.3 Assigning costs to the key production processes

The third step is to assign approximate costs to the key components of the production process. To achieve this, it may be appropriate to invite relevant members of the accounts staff to the production meeting.

At Green and Keen, the accounts staff proved useful in focusing the discussion so that appropriate costs could be assigned. Many of the process operators were previously unaware of these costs.

3.4 Presenting the findings

It is essential to present the findings in a format that will subsequently be useful. The Production Director at Green and Keen adopted two formats:

- a flow chart, designed using a software package and showing operators' initial comments on where the problems were arising (see Fig 3 overleaf);
- a table of costs (see Table 5 overleaf).

The flow chart provided the basis for more detailed process flow charts in the main problem areas.

Table 5 proved valuable in that:

- It showed clearly the difference in cost between a fault resulting in the loss of an expensive bench-top and one resulting in the loss of a relatively inexpensive leg support.
- It also confirmed the overall high cost of wasted production. Over £38 000 was being wasted each year due to the issues of customer returns, leg-support assembly scrap and other causes. This does not include the cost of shipping the customer returns (nearly £4 400) or skip charges (£4 500); the total cost was probably over £47 000. This calculation produces a result that is within 10% of the initial estimate given in Section 2.2, which was based on limited data (ie production rejects over two weeks and customer complaints over six months).

Fig 3 Flow chart and operators' initial comments on where problems were arising

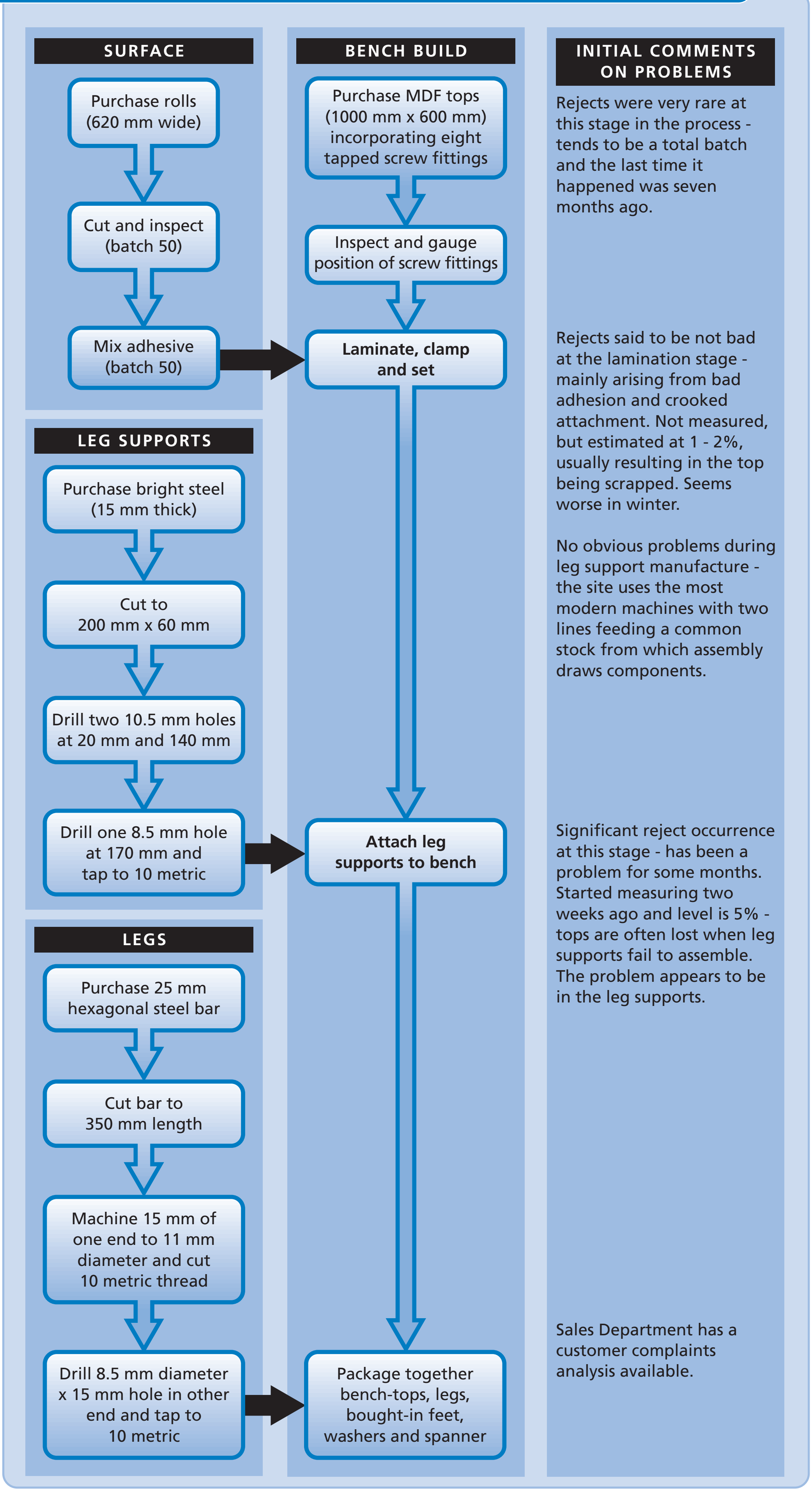


Table 5 Manufacturing costs at Green and Keen

Material and process costs	Cost/bench sold (£)	Cost/year (£)	Waste/year* (£)
Top manufacture			
Tops purchased	7.31	80 445	6 700
Surface material metres	1.72	18 899	2 400
Cut and inspect pieces	1.36	15 000	1 904
Prepare adhesive - batches 50 benches	1.36	15 000	n/i
Adhesive for batches 50 benches	2.00	22 000	n/i
Lamination costs	3.18	35 000	2 920
Total	**16.93**	**186 344**	**13 924**
Manufacture of leg support			
Leg support materials	1.14	12 540	1 271
Leg support machining	4.41	48 515	4 840
Total	**5.55**	**61 055**	**6 111**
Leg manufacture			
Leg material	6.13	67 467	6 747
Leg machining	8.95	98 501	9 876
Total	**15.08**	**165 968**	**16 623**
Assembly			
Leg support assembly	3.18	35 000	1 750
Total	**3.18**	**35 000**	**1 750**
Packing, miscellaneous			
Packing/warehousing labour	4.55	50 000	n/i
Packing materials	0.80	8 800	n/i
Miscellaneous	9.89	108 820	n/i
Total	**15.24**	**167 620**	
Total budget cost/manufacturing cost	***55.98***	***615 987***	***38 408***

n/i = not identified

* The waste/year figures were calculated by subtracting the total amount of raw materials purchased (not shown) from the amount included in benches sold.

Study Industry Example 4 in GG223 to see how one company used process mapping to identify where in its process waste was arising.

Where should you focus first?

Section 4 shows you how to construct and interpret a simple Pareto diagram to identify those components of your process most in need of attention and, perhaps, change.

4.1 Plotting a graph to show priorities

The most useful way of identifying where you should focus first to reduce your waste is to use a simple, but clever, technique called Pareto analysis.

Pareto analysis: a step-by-step approach

Step 1 Gather the necessary data for the parameters you are measuring. In the case of Green and Keen, the data used related to the cost of customer complaints, presented as a simple value per unit. Other companies considering the cost of complaints may need to take into account cost variations with batch size, customer location etc. Pareto analysis can also be used to measure a range of other parameters, for example quantities of waste in different categories (see Good Practice Guide (GG223) *Preventing Waste in Production: Industry Examples*).

Step 2 Sort the data in descending order of value, as in Table 6.

Step 3 Calculate the percentage of the total associated with each component being measured. In the case of Green and Keen, the calculation was the total cost for each category of complaint as a percentage of the total cost to the company of all complaints.

Step 4 Calculate the cumulative percentage from the percentages derived in Step 3.

Step 5 Draw a graph, as in Fig 4:

Plot the parameters measured (causes of complaint for the Green and Keen example) on the x axis.

Plot the percentages derived in Step 3 against the left-hand y axis, using an appropriate scale, and draw a histogram for each parameter.

Plot the cumulative percentage derived in Step 4 against the right-hand y axis, using a scale of 0 - 100% and working from the mid-point of each bar. Connect the points plotted to form a curve.

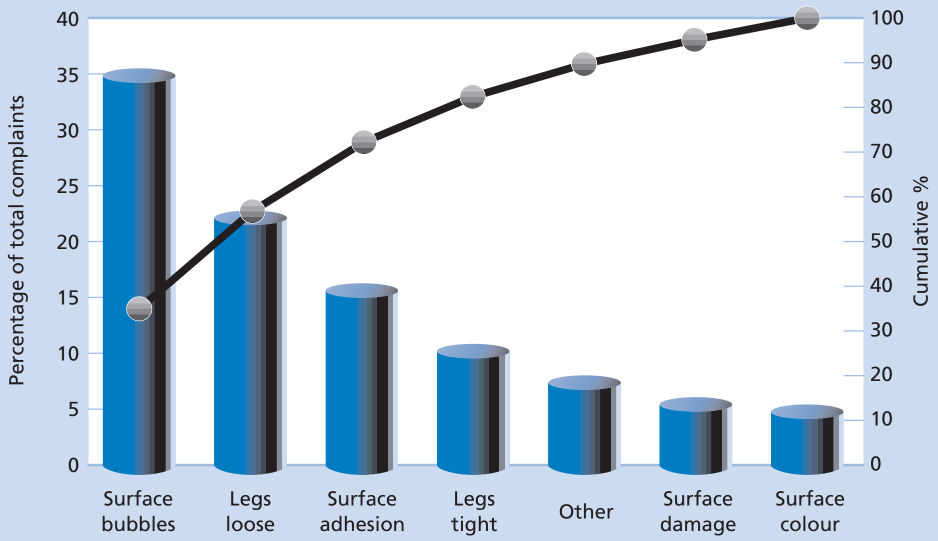
Most spreadsheet programs can produce these Pareto diagrams from spreadsheet tables. The combination of simple and cumulative percentage data in one diagram helps you to identify and separate the few items (problems) that are important from the many that are individually less significant.

NB: Pareto diagrams are often called ‘80:20 diagrams’ on the basis of the rule of thumb which says that, for almost anything that occurs, 80% of the results will be caused by only 20% of the events.

Table 6 Ordered 'Pareto' table of complaints over six months by cause

Complaint	Number	Value (£)	Transport cost (£)	Total cost (£)	Cost as % of total	Cum %
Surface bubbles	76	56	10	5 016	34.9	34.9
Legs fit too loosely into bench-top	48	56	10	3 168	22.0	56.9
Surface adhesion	34	56	10	2 244	15.6	72.5
Unable to fit legs into bench-top	22	56	10	1 452	10.1	82.6
Other	16	56	10	1 056	7.3	89.9
Surface damage	12	56	10	792	5.5	95.4
Surface colour	10	56	10	660	4.6	100.0
Total	**218**			**14 388**		

Fig 4 Pareto diagram of customer complaints by cause



4.2 Drawing conclusions and taking the next steps

Drawing conclusions from a Pareto diagram is relatively simple. In the Green and Keen example, the diagram showed clearly that the first four causes of complaint (surface bubbles, legs fit too loosely into bench-top, surface adhesion and unable to fit legs into bench-top) represented more than 80% of the costs associated with customer complaints.

These findings tied in well with the process flow chart, in which operators had identified laminating (bars 1 and 3 in Fig 4) and leg support assembly (bars 2 and 4 in Fig 4) as common causes of production rejects.

In the light of these findings, two separate projects were initiated:

- Project 1: an investigation of leg support production and assembly;
- Project 2: an investigation into the bench-top laminating process.

Study Industry Examples 1, 3, 4, 5, 6 and 7 in GG223 to see how companies used histograms and Pareto diagrams to identify where they should focus their attention first.

What are the possible causes?

Section 5 uses the Green and Keen Industry Example to demonstrate how a company can identify the possible causes of waste. Particular points highlighted include:

- the importance of drawing on staff expertise, for instance, by using brainstorming techniques;
- the need to check whether waste is caused internally or is associated with faults in bought-in materials/parts;
- the value of tally sheets, scattergrams, process maps, cause and effect diagrams and brainstorming to pinpoint more accurately the main in-house problem areas.

5.1 Project 1: leg support production and assembly

Team 1 (machinists and assemblers involved in leg support production and assembly at Green and Keen) immediately identified the basic problem. In the case of a 'rogue' leg support, once the first screw had been inserted, the hole for the second screw would not line up accurately with the fitting supplied in the bench-top. Because the production staff used power tools, cross-threading often occurred, causing irreparable damage to the fitting in the bench-top.

Two possible causes were considered:

- bought-in bench-tops failing to meet the specification set;
- an in-house machining problem.

Checks on the consistency of the position of tapped fittings in the bought-in bench-tops showed these to be well within the specification set, confirming that the problem lay in-house.

Assembly staff pointed out that, if a poor fit was spotted in time (ie before cross-threading occurred), they could often assemble a different leg support into the same bench-top without difficulty. This indicated a possible problem with the positioning of holes in the leg supports.

In a team brainstorming session, the machinists suggested that the problem might be occurring on only one of the two production lines (Line A and Line B), and that it might vary with operator or time of day. The following procedure was used for eight days to obtain more detailed information about the source of the rejects and the time of day at which they occurred:

- The machined supports were stored in bundles. Each bundle represented two hours' worth of production and was labelled with its origin (Line A or B) and the time of its production (1st, 2nd, 3rd or 4th quarter of the shift).
- Any rejects were recorded at the assembly stage on a tally sheet (see Table 7).
- The data were transferred to an analysis spreadsheet in the form of individual production line tables (see Table 8).
- The data from the production line tables were plotted on two scattergrams (see Fig 5).

The diagrams produced for Green and Keen showed that the problem occurred mainly on Line B and mainly in the second half of the shift. Although the underlying cause was not immediately obvious, the findings suggested that the process was not operating consistently.

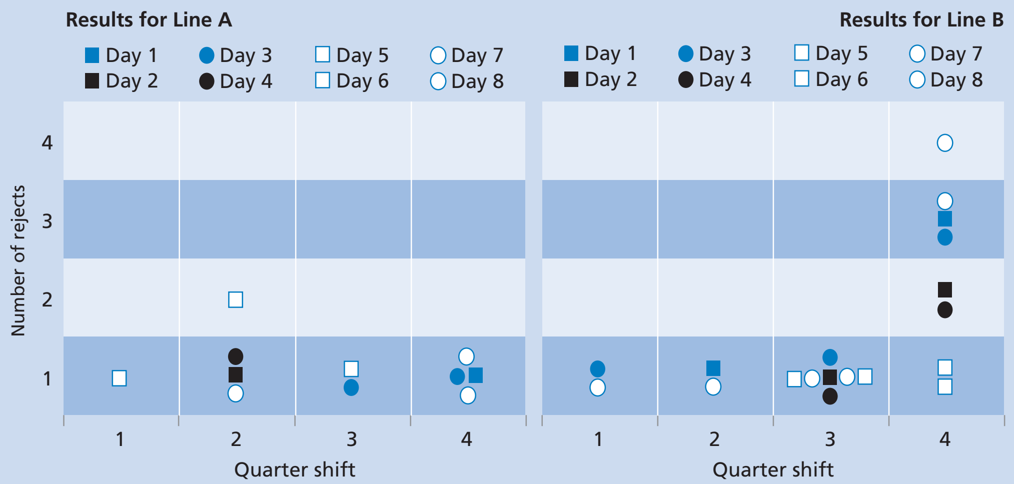
Table 7 Tally sheet

Shift		Date
Assembly operator		
Source of reject		
Line A	**Count**	
1st quarter of shift		
2nd quarter of shift		
3rd quarter of shift		
4th quarter of shift		
Line B	**Count**	
1st quarter of shift		
2nd quarter of shift		
3rd quarter of shift		
4th quarter of shift		

Table 8 Analysis spreadsheet

Line A	**Quarter**				**Line B**	**Quarter**			
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
Day 1				1	Day 1		1		3
Day 2		1			Day 2			1	2
Day 3			1	1	Day 3	1		1	3
Day 4		1			Day 4			1	2
Day 5	1		1		Day 5			1	1
Day 6		2			Day 6			1	1
Day 7				1	Day 7	1		1	4
Day 8		1		1	Day 8		1	1	3

Fig 5 Scattergram of rejects for each production line



5.2 Project 2: bench-top laminating process

5.2.1 Defining the problem

The Pareto diagram in Section 4 had already shown that surface bubbles were the main cause of the costs arising from customer complaints (34.9%), with surface adhesion also being a significant problem (15.6%).

Team 2 (staff responsible for glue preparation, veneer cutting and laminating) was certain that both laminating and assembly staff would notice obvious defects and would scrap any defective bench-tops before they left the factory. Its first task was, therefore, to inspect the rejects and determine the nature of the defects.

5.2.2 Identifying the causes

Team 2 initially thought that the problems might be developing several days after laminating, while the glue was drying out and curing. The glue was either failing completely or producing gas: possible reasons included a faulty batch of glue, a dirty surface or the effect of moisture content.

The team produced a detailed map of the laminating process (see Fig 6) and then constructed a cause and effect diagram (also known as an Ishikawa or fishbone diagram). A skeleton fishbone diagram shows the undesirable result (in this case bubbles and adhesion problems) plus four headings under which possible causes can be considered (Machinery, Methods, Materials and Men). Staff at Green and Keen made suggestions under each heading during a brainstorming session, recording them on removable sticky labels and adding them to the skeleton. The most appropriate suggestions were incorporated into a final diagram (see Fig 7).

Fig 6 Process map for lamination

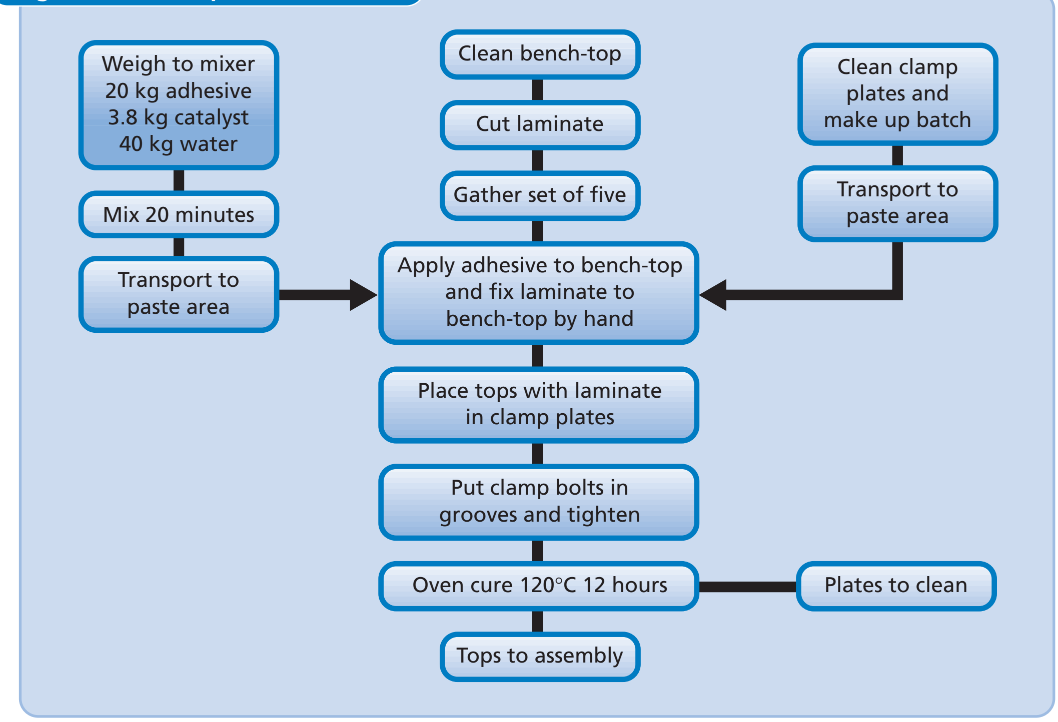
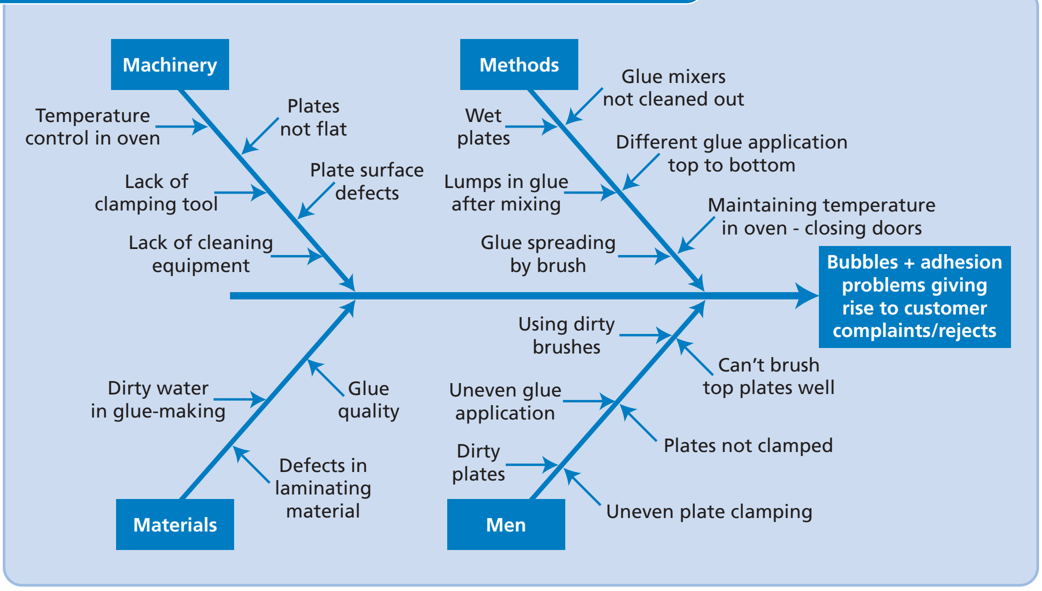


Fig 7 Cause and effect diagram for the laminating process



Combining a cause and effect diagram with brainstorming often throws up plausible suggestions that can be investigated subsequently. However, participants are more likely to contribute to the discussion if it is clearly a 'no blame' exercise. Another useful approach is to encourage participants to ask 'Why?' five times in succession as a means of getting to the root cause of any problem. In the Green and Keen example, this might work as follows:

Problem? Uneven glue application.
Why? Because the brushes apply the glue unevenly.
Why? Because they are dirty and choked.
Why? Because they are not cleaned.
Why? Because they are old and too difficult to clean.
Why? Because the company will not buy new ones.

While this does not necessarily reach a definitive conclusion, it does raise questions on brush supply and cleanliness, and on whether or not brush application of the glue is appropriate.

The Green and Keen cause and effect diagram generated a number of ideas. More specifically, it focused particularly on glue application as a possible cause of the problem.

Team 2 decided to explore this further in a two-stage brainstorming session:

- Stage 1: Gathering ideas - everyone to write their suggestions for improved glue application, however 'off-the-wall', on removable sticky labels and stick them on a blank flip-chart sheet. Nobody to comment on any of the suggestions except to build on them.
- Stage 2: Evaluating ideas - everyone to comment on the practicability and usefulness of the suggestions made, the aim being to narrow down the list of ideas to the feasible few.

Table 9 overleaf summarises the final short list.

Table 9 Suggested solutions to glue application problems

Objective	The more even distribution of glue on the surface of the plate
Suggestions	■ Always use a new brush ■ Use a spray ■ Dip the plates ■ Buy pre-glued laminate ■ Use thinner glue ■ Use different glue ■ Use steps for applying glue to the upper plates ■ Apply the glue using a roller ■ Maintain a constant stack height ■ Always use tall staff for the gluing process ■ Buy pre-mixed glue ■ Buy laminated bench-tops ■ Use a better brush cleaner

5.2.3 Backing up the suggestions with data

The Green and Keen Production Director decided to back up Team 2's suggestions with some relevant data. He was particularly interested in assessing two possibilities:

- whether the position of the laminating plate was affecting glue spreading and the formation of bubbles;
- whether early signs of bubble formation might be present at the assembly stage or when the laminated tops were removed from the clamps, even though the full problem might not develop for several days.

A visit to the laminating and assembly areas confirmed that several bench-tops had a handful of very small bubbles, 1 mm or so in size. So, Team 2 designed a tally sheet on which laminators could record the occurrence of these 'seed' bubbles when the bench-tops were removed from the clamps and sent for assembly. The bubbles were recorded for each of four sections of each plate, with Section 1 being furthest from the operator applying the glue and Section 4 the closest. Tables 10 and 11 are based on data from the tally sheets. Table 10 summarises data for Section 1 for a one-week period (equivalent data were recorded for Sections 2, 3 and 4). Table 11 shows the total number of bubbles for all sections of the laminated sheets.

Table 10 Summary of bubbles recorded in Section 1 of the laminated sheets

Date	Mon	Tues	Wed	Thur	Fri	Week
Total output of bench-tops	45	47	52	52	38	234
Number of bubbles recorded in Section 1						
Top plate	17	12	21	19	14	83
Plate 2	11	8	9	13	10	51
Plate 3	9	7	3	7	12	38
Plate 4	6	4	7	5	6	28
Bottom plate	7	6	5	8	7	33
Total Section 1	**50**	**37**	**45**	**52**	**49**	**233**

Table 11 Total bubbles recorded for all sections of the laminated sheets

Date	Mon	Tues	Wed	Thur	Fri	Week
Top plate	75	63	83	66	80	367
Plate 2	50	45	53	49	50	247
Plate 3	38	32	31	35	46	182
Plate 4	25	19	29	19	31	123
Bottom plate	24	27	19	26	20	116
Total	**212**	**186**	**215**	**195**	**227**	**1 035**

The findings over a one-week period showed 1 035 bubbles in 234 tops, an average of 4.4 bubbles/top. Scattergrams drawn from the tables highlighted two conclusions:

- Nearly four times as many bubbles were present in the top plate of the clamped 'sandwich' sent to the curing oven as in the bottom one (see Fig 8). This supports one of the possible causes of rejects identified on the fishbone diagram: that some difficulty is experienced in applying glue to the top plate ('Can't brush top plates well').
- Section 1 - which is furthest from the operator applying the glue - appeared to produce fewer bubbles than the other three sections (see Fig 9). This was the opposite of what was expected.

Fig 8 Scattergram showing laminating defects by plate position

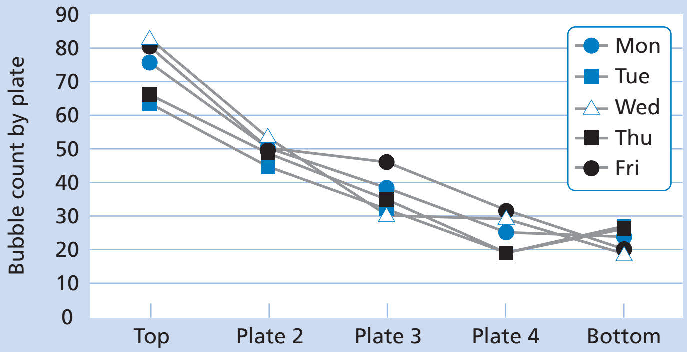
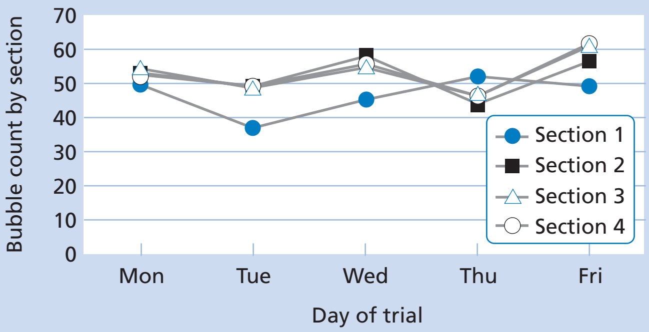


Fig 9 Scattergram showing laminating defects by section



Study Industry Example 3 in GG223 for an application of a fishbone diagram. Industry Examples 1, 3, 5, 9 and 10 have used other approaches to identify the possible causes of process waste.

How consistent is your process?

Section 6 introduces the concept of process capability - a measure of how well a process is meeting the target specifications set by the industry concerned.

It then uses the Green and Keen Industry Example to calculate and interpret two capability values for each production line - the capability each line could achieve if it were correctly centred, and its capability in practice.

6.1 Introducing the 'capability' concept

Where a process component, eg a machining line, is not operating consistently, it is useful to carry out a capability assessment of that component.

Industrial companies usually set target specifications (or tolerances) for key attributes of their products, ie they specify the highest and lowest values that are acceptable. These specifications will depend on the level of consistency and accuracy required. The *capability* of a process is a measure of how well it can meet the specifications set. It determines the percentage of products rejected for being outside the specifications. A *capable* process is one that can meet the end-use specification most of the time. The more variable a process is, the less capable it will be.

To determine the capability of a process, it is important to understand some simple, but important, statistical concepts relating to variability and how it is measured. The most important of these are range, standard deviation and capability indexes. These are explained in Appendix 1.

Capability assessments can provide:

- confirmation of the possible cause of a problem;
- an immediate measure of production line performance - instead of waiting for rejects at the assembly stage;
- an accurate performance base-line against which future changes can be measured;
- a first step towards the rapid identification of subsequent process inconsistencies using control charts.

6.2 Determining the capability of the leg support machining process

Team 1 had already confirmed (see Section 5.1) that the incoming bench-tops were within the specification set, ie with leg support screw fitting centres 120 mm apart ± 0.1 mm. Checks were also made on:

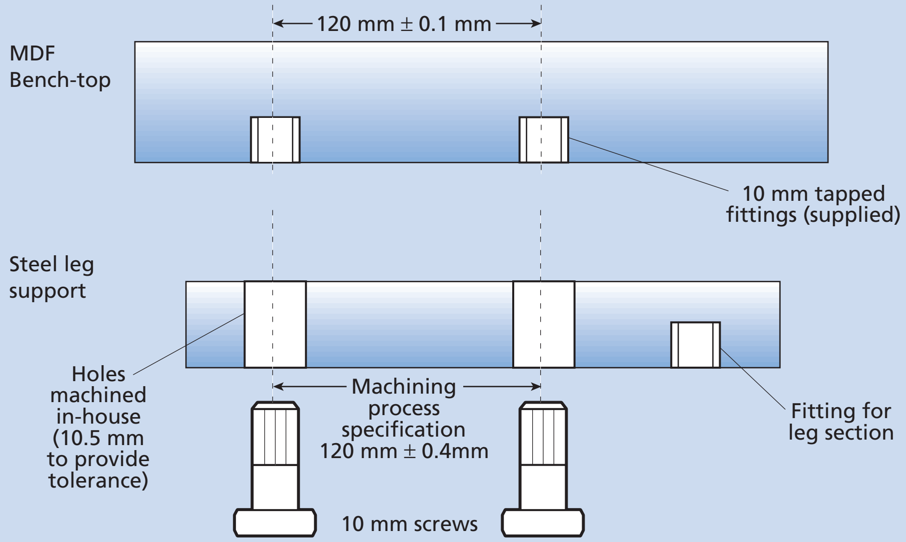
- internal gauge capability;
- the process specification.

The results of these checks were as follows:

- The gauging methods used internally to measure the holes in bench-tops and leg supports agreed with those used by the bench-top supplier.

- The process specification allowed the leg supports to be fitted to the bench-tops at the two specification extremes, ie when the bench-top hole centres were at their minimum permitted distance apart (ie 119.9 mm) and the leg support hole centres were at their maximum permitted distance apart (ie 120.4 mm), or vice versa (120.1 mm and 119.6 mm respectively), see Fig 10.

Fig 10 Machining and assembly process of leg supports to bench-top



Team 1 then calculated the capability of the leg support machining process by:

1. Measuring the distance between hole centres without adjusting the process. After two days, about 50 measurements were available for each production line (Line A and Line B). Table 12 shows a selection of these measurements.
2. Calculating the mean value - which indicated that Line A was 0.06 mm off-centre and that Line B was 0.08 mm off-centre (see Table 13 overleaf).

Table 12 Capability study measurements

	Shift quarter when measurement made	Line A measurement (mm)	Line B measurement (mm)
1	1	119.90	119.85
2	1	119.95	119.90
3	1	119.90	119.80
4	1	120.10	120.05
⁄\⁄	⁄\⁄	⁄\⁄	⁄\⁄
44	4	120.25	120.45
45	4	120.00	120.25
46	4	120.00	120.35
47	4	120.15	120.30

3. Calculating the standard deviation for the data (see Table 13 and Appendix 1). The standard deviations of 0.224 mm (Line B) and 0.135 mm (Line A) show that Line B is more variable than Line A.

Table 13 Parameters used to determine capability

	Line A	Line B
Mean (mm)	120.06	120.08
Standard deviation (mm)	0.135	0.224
Target mean (mm)	120.00	120.00
Upper limit of specification (mm)	120.40	120.40
Lower limit of specification (mm)	119.60	119.60

4. Calculating the capability index Cp (see Appendix 1) to show how well the process can meet the specification if it is centred correctly. Cp compares the specification range with the variation around the mean as indicated by the standard deviation. The smaller the standard deviation is, in comparison to the range between the upper and lower limit of the specification, the more product that will be within the specification. The Cp calculations for Line A and B are outlined below:

$$Cp = \frac{\text{upper limit of specification} - \text{lower limit of specification}}{\text{Standard deviation} \times 6}$$

$$Cp \text{ (Line A)} = \frac{120.40 - 119.60}{0.135 \times 6}$$

$$= \frac{0.80}{0.81}$$

$$= \mathbf{0.99}$$

$$Cp \text{ (Line B)} = \frac{120.40 - 119.60}{0.224 \times 6}$$

$$= \frac{0.80}{1.34}$$

$$= \mathbf{0.60}$$

By convention, a Cp of 1.0 means that the process is theoretically capable. In other words, if it is correctly centred, only 0.3% of the production output will be outside the specified tolerance limits (see Appendix 1).

The value for Line A shows that it is just capable, theoretically, of meeting the specification. However, Line B, with a Cp of 0.60, has serious problems. If Line B had a Cp of 0.67, 4.6% of its output would be outside the specified tolerance limits. In fact, the performance of Line B is even worse.

In practice, real processes are not centred exactly, so it is usual to aim for a Cp value of at least 1.3 (ie that the standard deviation is 12.5% of the specification range). This provides some leeway, allowing the process to drift a little off-centre while still meeting the specification most of the time.

5. Calculating the capability index Cpk (see Appendix 1) to show how well the process is centred within the specification range. This is done by comparing the mean with the upper and lower points of the specification and relating this to the variation within the products (as indicated by the standard deviation).

$$Cpk = \frac{\text{the smaller of D1 and D2}}{\text{Standard deviation} \times 3}$$

where

D1 = Upper specification – mean value
D2 = Mean value – lower specification

Line A

D1 = 120.40 – 120.06
= 0.34 mm

D2 = 120.06 – 119.60
= 0.46 mm

$$Cpk = \frac{0.34}{0.41}$$

= **0.83**

Line B

D1 = 120.40 – 120.08
= 0.32 mm

D2 = 120.08 – 119.60
= 0.48 mm

$$Cpk = \frac{0.32}{0.67}$$

= **0.48**

By convention, a Cpk of 1.0 means that the process is reasonably well centred, however, increasing Cpk above 1.0 will further reduce the number of products not meeting the specification.

It is clear from these values that Line A is performing below its theoretical capability because it is off-centre. Every measured value that is more than 0.83 × three standard deviations (ie 2.49 standard deviations) above the measured mean will be out of specification. Statistical tables indicate that this represents a rejects level of towards 1%.

Line B is performing worse, with a Cpk of 0.48. Statistical calculations and tables suggest that about 8% of the output of this production line will be above the upper specification limit. Line B also experiences a significant deterioration later in each day.

As indicated for Cp, the preferred value for Cpk for both lines is usually closer to 1.3, the value at which they would easily meet process specifications and keep scrap levels to a minimum.

Having performed these calculations, Team 1 understood the following:

- the low value of Cpk meant that the lines were not performing satisfactorily and action needed to be taken;
- the low value of Cp for Line B suggested that there was one or more causes of significant variability in the line;
- the off-target means (causing a lower value of Cpk than Cp) being present on both Line A and B indicated that there may have been a second factor causing this problem;
- the current values of Cp and Cpk against which to measure future improvement were 0.99 and 0.83 for Line A and 0.60 and 0.48 for Line B.

Study Industry Example 2 in GG223 to show how one company undertook a capability assessment of its process.

How can your process be improved?

Section 7 uses the Green and Keen Industry Example to show what actions might be taken once the capability of a process has been determined.

7.1 Actions to improve the performance of the leg support machining process

Where a Production Director identifies a poor process capability (see Section 6), the obvious way forward is to focus first on the main areas of poor performance. In the Green and Keen Industry Example, Line B is obviously performing very badly.

It is also worth considering whether performance that is potentially 'acceptable', as Line A would be if correctly centred (ie has a higher Cpk), could nevertheless be improved by making simple engineering modifications.

The first action taken at Green and Keen was a maintenance check of production Line B. This check identified:

- a bearing that was overheating and on the point of collapse;
- badly worn drill guides.

Both were immediately replaced, and the line was then run for a couple of days, with checks on temperature and vibration. The drill bearings on Line A were also changed as a precautionary measure.

To check the effectiveness of replacements and repairs, it is important to carry out a second capability study. A quick one-day repeat study at Green and Keen showed that each line now had a Cp value of just over 1.0 (see Table 14). These new measurements were perceived to be an appropriate basis for introducing control charts (see Section 8).

Table 14 Mean, standard deviation and capability values after remedial engineering work

	Line A	Line B
Mean (mm)	120.04	120.004
Standard deviation (mm)	0.119	0.127
Cp	1.12	1.05
Cpk	1.01	1.04

Where a poor capability is the result of equipment deterioration, it is important to determine why the deterioration has occurred. At Green and Keen, a 'healthy discussion' on the topic highlighted the following:

- all the company fitter's time was taken up with 'fire-fighting' - fixing equipment as it broke down to minimise production downtime;
- the fitter had no capacity for anything more than rudimentary preventive maintenance, so equipment gradually deteriorated;

- time spent maintaining the machining lines reduced the time spent keeping the laminating oven operational.

7.2 Actions to improve the performance of the laminating process

The progress made in identifying the causes of the laminating problems at Green and Keen (see Section 5.2) encouraged the introduction of two major changes:

- modifications to the bench and working position so that all plates are at a convenient height for coating with glue;
- improvements to the arrangements for glue mixing and plate cleaning.

A subsequent spot check showed that these changes had reduced the level of 'seed' bubbles by a factor of two, to about two per bench-top. This was expected to give a similar level of reduction in customer complaints.

However, the laminating team believed that further improvements could be achieved. It set up experiments on glue viscosity, glue application techniques and curing conditions and, as a result of the findings, introduced a number of further changes and improvements. (The design and conduct of experiments is covered in some of the books listed in Section 9.)

To confirm the level of improvement achieved, staff took measurements over a one-week period using the tally sheet developed for the initial diagnostic investigation (see Section 5.2). Every set of five bench-tops leaving the laminating clamps was inspected for bubbles. The overall average concentration of defects in a one-week period had fallen from 4.4 bubbles per bench-top (see Section 5.2.3) to 1.02 bubbles per bench-top (see Table 15).

Table 15 Total bubbles recorded for all sections of the laminated sheets following improvements to the laminating process

Date	**Mon**	**Tues**	**Wed**	**Thur**	**Fri**	**Week**
Total output of bench-tops	43	51	50	51	47	242
Number of bubbles recorded						
Top plate	8	11	12	11	6	48
Plate 2	9	10	9	10	13	51
Plate 3	11	11	8	13	11	54
Plate 4	10	10	9	12	10	51
Bottom plate	8	10	7	10	7	42
Total	**46**	**52**	**45**	**56**	**47**	**246**

Study Industry Example 2 in GG223 to find out how one company made process changes and then rechecked its process capability.

How can you maintain control?

Section 8 introduces the concept of control charts to maintain control once a process is operating satisfactorily. It then uses data from the Green and Keen Industry Example to construct two types of control chart and explains how each should be interpreted.

8.1 The concept of control charts

Where remedial work improves the capability of a process, it is essential to remember that low reject levels will be maintained only if there is no deterioration in the equipment used and if the operators maintain the control settings correctly.

It may be possible to initiate procedures that include the recording of rejects on tally sheets or encouraging machinists to look out for problems and adjust the machines accordingly. This type of approach has its disadvantages:

- once parts are rejected, waste has been incurred;
- machinists may make unnecessary changes to machines or methods.

Another option is to use control charts, which are simple both to construct and to use. The procedure is as follows:

1. Take a significant number of measurements from the process.
2. Use simple equations to calculate an Upper Control Limit (UCL), a Lower Control Limit (LCL) and a Centre Line (CL).
3. Draw on a chart the three horizontal lines that correspond to the UCL, LCL and CL values. The difference between the upper and lower control limits indicates the normal variation to be expected.
4. Regularly measure and plot the performance of the process on the chart.

If the measured value stays well within the two boundary lines (UCL and LCL) and shows no particular trend, your process is under control and you need not take any action.

If the measured values gradually move away from the CL towards one of the limits or passes one of the limits, this may indicate that your process needs attention.

There are several types of process control chart, each plotting slightly different variables and each using different statistical rules to calculate the LCL, CL and UCL values. Further details are given in Appendix 2.

8.2 Using process control charts to maintain control of the leg support machining process

The Green and Keen Production Director introduced the ‘x-bar R’ chart as a means of maintaining control of the leg support machining process. The x-bar R chart is really two separate charts, one for plotting the mean value and one for plotting the range.

The procedure required is as follows:

1. Take small samples of measurements at regular intervals.
2. Calculate the mean value (x-bar) of the measurements in each sample.
3. Calculate the range of values measured (the difference between the largest and the smallest measurement in each sample).
4. Plot each result on an 'x-bar R' chart.

Certain decisions also have to be made at the start:

- How large a sample should be taken?
- How often should sampling take place?
- Where should the control limits be set?

It is important to remember that, although increasing the sample size improves accuracy, more time is involved in taking that sample.

At Green and Keen, it was agreed that samples would be taken twice each day (during the first and last quarters of a shift) with four measurements taken per sample - a level that would give a reasonable indication of any changes taking place.

The control limits were derived from measurements taken after remedial work had been carried out on the two production lines (see Section 7). The measurements were divided into 'samples', with four measurements to each sample (see Table 16). The mean value (x-bar) and the range ($x_{maximum} - x_{minimum}$) were calculated by production line for each sample set and for the 24 sample measurements (see Table 17 overleaf).

Table 16 Measurements taken after engineering work, divided into six sample sets

Set	Reading	Line A (mm)	Line B (mm)
1	1	119.95	119.85
1	2	119.95	119.90
1	3	119.90	119.85
1	4	120.10	120.00
2	5	120.20	120.10
2	6	120.20	120.10
2	7	119.95	119.85
2	8	119.95	119.85
3	9	119.95	119.85
3	10	120.20	120.10
3	11	119.90	120.05
3	12	120.20	120.15
4	13	120.10	120.00
4	14	120.20	120.20
4	15	119.95	119.85
4	16	120.00	119.90
5	17	120.05	120.00
5	18	119.90	120.20
5	19	120.10	120.15
5	20	119.85	120.10
6	21	120.15	120.15
6	22	120.20	120.05
6	23	120.00	120.00
6	24	120.00	119.85

Table 17 Mean value and range for each sample set and for all samples (mm)

Set	Line A		Line B	
	Mean	Range	Mean	Range
1	119.98	0.200	119.90	0.150
2	120.08	0.250	119.98	0.250
3	120.06	0.300	120.04	0.300
4	120.06	0.250	119.99	0.350
5	119.98	0.250	120.11	0.200
6	120.09	0.200	120.01	0.300
Overall	**120.04**	**0.242**	**120.00**	**0.258**

The mean and range values, plus various constants derived by statisticians for the purpose, were used to derive the centre line and the upper and lower control limits of the charts. The relevant equations are given in Appendix 2.

The values derived from the figures in Table 16 were:

Line A

x-bar chart (mean)

UCL = 120.22
CL = 120.04
LCL = 119.86

R chart (range)

UCL = 0.55
CL = 0.242
LCL = zero

Line B

x-bar chart (mean)

UCL = 120.19
CL = 120.00
LCL = 119.81

R chart (range)

UCL = 0.59
CL = 0.258
LCL = zero

Fig 11 shows the control limits for Line A drawn on a chart. The points plotted in this case are the mean and range values derived from the six sample sets for production Line A. A second chart was produced for Line B.

Fig 11 x-bar R chart

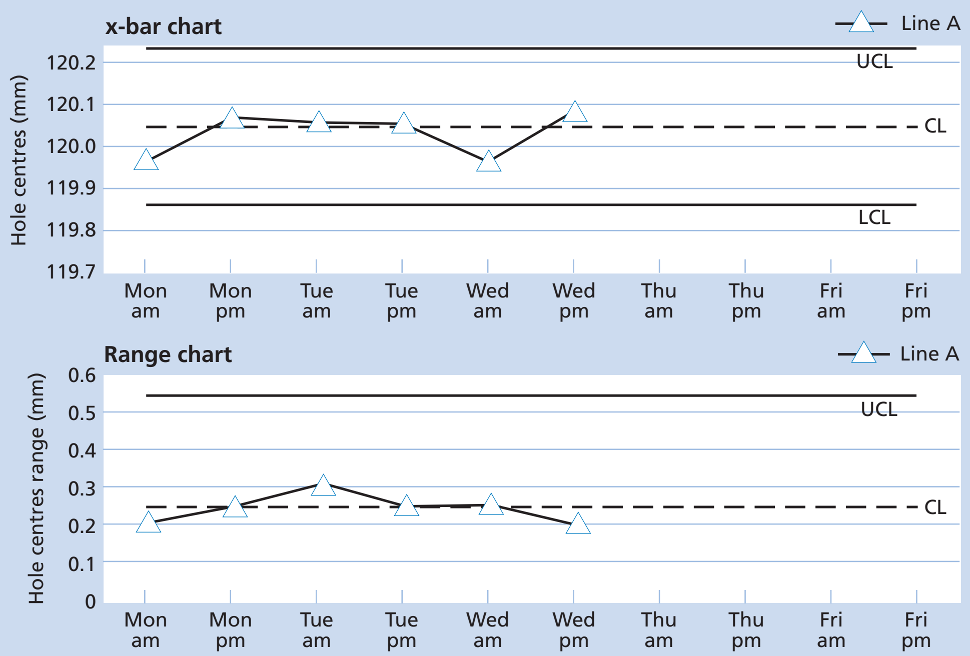


Chart interpretation can be summarised as follows:

- Where the plotted x-bar results fall between the upper and lower limits, no significant change is taking place within the process. In this example, this means that the mean distance between holes is not altering significantly.
- Any overall trend up or down on the graph indicates a methodical drift away from a centred process, even if the range chart stays within the control limits set.
- If the plotted range results hit the upper limit, the process is becoming more erratic. Even if the mean stays on target, some items will be outside the specification set.
- The combination of drift and a more erratic process indicates a deterioration in process capability and should initiate remedial action.

8.3 Using process control charts to maintain control of the laminating process

The Green and Keen Production Director introduced the c chart to ensure that the level of improvement achieved in the laminating process was maintained. The c chart is the most appropriate for recording changes where the key measurement is a discrete variable (bubbles on a single bench-top) involving whole number values, and where the units examined (the bench-tops) are a constant size.

The decision was taken to inspect one set of five bench-tops each day, at a time chosen at random. This random choice of timing was acceptable because the main special cause of variation was expected to be glue quality - and a single batch of glue lasted for a whole day.

The control chart variable to be plotted (c) was defined as *'the number of defects in a set of five bench-tops'*.

The control limits for the chart were derived using the equations given in Appendix 2, page 43:

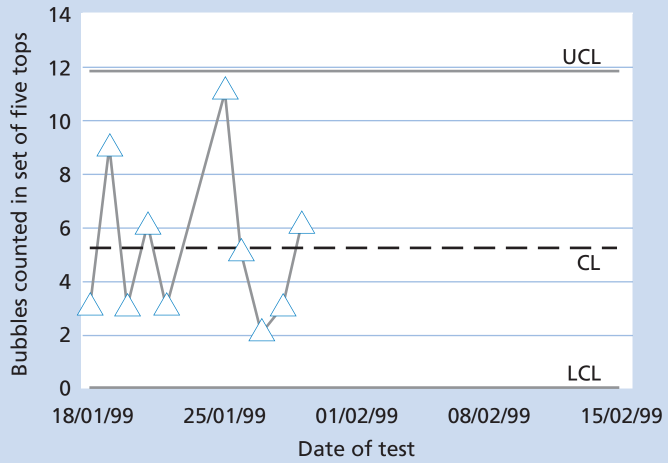
UCL = 11.88
CL = 5.10
LCL = -1.68 (corrected to zero as a negative concentration is physically meaningless)

Over the next two working weeks, the laminating staff selected one sample set of five bench-tops to inspect each day, noted the total number of bubbles in the set (see Table 18) and plotted the result on the control chart (see Fig 12 overleaf). The chart showed that, despite an element of scatter about the centre line, the process was staying in control. Furthermore, there was no evidence of any drift away from the CL value of 5.1 bubbles per set of five bench-tops.

Table 18 Bubbles recorded in the selected samples

Date	Time	Number of bubbles
18 Jan	09:00	3
19 Jan	10:00	9
20 Jan	11:00	3
21 Jan	12:00	6
22 Jan	14:00	3
25 Jan	15:00	11
26 Jan	16:00	5
27 Jan	17:00	2
28 Jan	09:00	3
29 Jan	10:00	6

Fig 12 A c control chart for lamination bubble defects per set of five bench-tops



8.4 Control charts: a simple solution

Two factors help process operators to overcome their often natural aversion to using numerical techniques:

- control charts are based on very simple principles;
- control chart applications do not require an understanding of statistics - just the following of a simple procedure.

However, staff can benefit from a better understanding of the subject as this would allow them to identify more subtle trends. It would also encourage them to apply the same methods to different types of problem which might arise in the future. More theory and practical examples are given in Appendix 2 and the references in Section 9.

8.5 Further applications

The Green and Keen example represents a common application of statistical process control. It is essentially a manual task, although numerous computer programs are available which help to reduce the tedious calculations, produce graphical output and so on.

Many manufacturing processes are controlled by automation systems which receive, analyse and store much valuable information about the process. Increasingly, statistical process control analysis is becoming available as part of an automation system, or as a separate module which can be integrated within that system. This is a viable technique where the variable on which the statistical analysis is based is capable of being measured automatically. It has the benefit of providing continual indication, on-line, of the quality performance of the process.

Study Industry Examples 5 and 8 in GG223 to find out how companies have used control charts to maintain control of their processes.

Further reading

SPC Simplified: Practical Steps to Quality by Amsden, Butler and Amsden. Published by Quality Resources. ISBN 0-527-91617-X

Histograms, SPC, brainstorming, cause and effect. Very little theory or statistics but lots of good examples.

Statistical Process Control (SPC). Published by Chrysler, Ford and General Motors.

This is how you must do it as a supplier to these three motor industry majors. Copies from Carwin Continuous Ltd, Unit 1 Trade Link, Western Avenue, West Thurrock, Grays, Essex RM20 3FJ (Tel: 01708 861333). This forms a part of the set of books that make up the guides to QS9000 motor industry certification.

Statistics for Experimenters by Box, Hunter and Hunter. Published by John Wiley. ISBN 0-471-09315-7

A heavyweight, detailed book on this subject.

100 Methods for Total Quality Management by Kanji & Asher. ISBN 0-8039-7747-6

Defines and describes minimally most of the quality acronyms and techniques. Excellent bibliography and good references to many of the techniques contained in the text. Not a detailed 'how to do it' guide.

Improving Competitiveness through Control. Published by the DTI's Advanced Control Technology Transfer (ACTT) Programme.

This guide introduces statistical process control and a variety of other process control techniques and how they can be used. Available free-of-charge from the DTI (Tel: 020 7215 1344, Fax: 020 7215 1518).

Statistical Process Control, 3rd Edition by John S Oakland. Published by Butterworth Heinmann, 21 May 1999. ISBN 0-750-64439-7.

This text provides the foundations of good quality management and process control, covering all theory and techniques. Also available in hardback.

Variability

The theory

If you try to repeat something exactly several times, you will find that the results of each attempt are not exactly the same - although the differences may be small. Variability is, therefore, inevitable.

There are two main causes of variability:

- 'normal' or 'common' causes, which are a random feature of the world we live in and are beyond our control;
- 'special' or 'assignable' causes, which are individually significant or identifiable.

Recognising the difference between these two types of cause is an important part of getting the best results. Common causes can be reduced only by identifying the inherent limitations of the manufacturing process, and ways to improve accuracy. Special causes can be reduced by identifying the change or process failure and implementing rapid corrective action.

Fig A1.1 Plot of random sample showing the typical bell-shaped curve

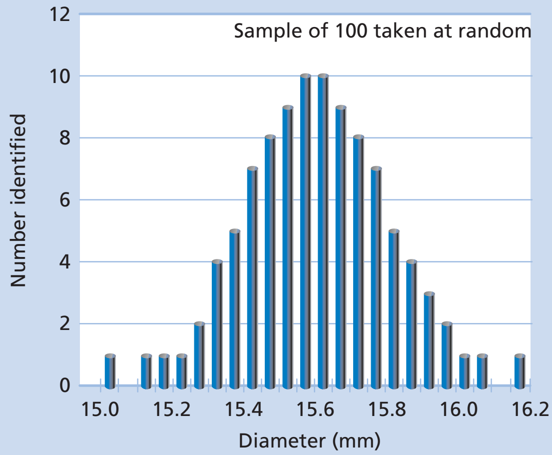
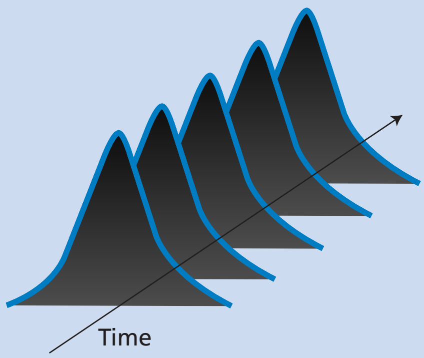


Fig A1.2 Distribution curve for a process running in control



Normal and special causes of variation

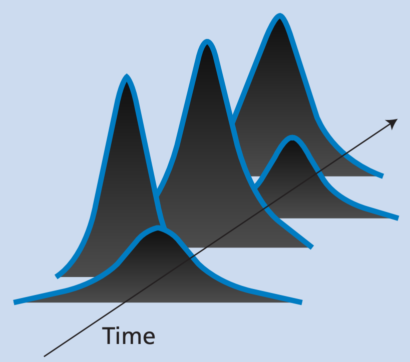
A process is said to be in statistical control if it produces a predictable pattern of results. For instance, a series of components being machined on a lathe will have some variation in diameter. This is inevitable and an analysis of the measured diameters will generate a distribution curve similar to that shown in Fig A1.1.

This variation is due to the tolerances of the lathe, the skill of the operator and so on. These are referred to as 'normal' or 'common' causes.

If a number of sets of samples are analysed over time, each set will exhibit a similar distribution curve. The height and width will be similar, as will the mean, as shown in Fig A1.2

However, in the real world other 'special' causes can also occur. These usually have one, or at the most a few, large sources of variability. They may be irregular, or unpredictable. They are certainly unwelcome. For example, the lathe may have a slight mechanical

Fig A1.3 *The effect of special causes of variation on the process*



failure, an operator may make errors in setting up the machine and so on. In this case, the sets of samples, if analysed as in the example above, do not exhibit similarity. The distribution pattern will change, as will the mean. The result is shown in Fig A1.3.

Clearly, in this situation, there is a fault that should be corrected. One of the main functions of statistical process control is to identify if the process is moving out of control (see Appendix 2 *Process control charts*).

Measuring variability

A goal for any manufacturing process is to reduce variation. In order to do so, the causes of that variation must be identified. A process which is in control is stable over time. It is subject to only normal causes of variation and, therefore, is the basis for further process improvement by reducing these causes. Statistical process control can be used to measure the degree of control and, therefore, the measure of improvement. Two useful measures of variability are:

- range;
- standard deviation.

The range is the difference between the maximum and the minimum values measured.

The standard deviation is a weighted indication of the curve's width - a measure of the spread. It is calculated as follows:

1. Determine the mean value (the sum of all the measured values divided by the number of values).
2. Subtract the mean from each individual value to find the difference.
3. Multiply each difference by itself to give the squared difference in each case.
4. Determine the mean squared difference or variance (the sum of all the squared differences divided by the number of measurements (n), or for samples of less than 30 measurements, n – 1 is regularly used).
5. Calculate the square root of the variance: this is the standard deviation.

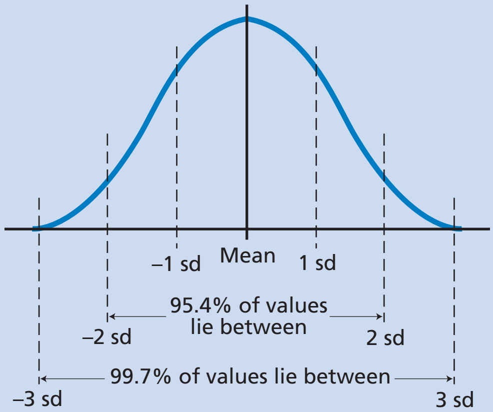
This can be expressed for samples of greater than 30 measurements by the following:

$$s = \sqrt{\sum \frac{(X_i - \bar{X})^2}{n}}$$

where s is the standard deviation, X_i are the individual readings, $\bar{X}$ (x-bar) is the sample mean and n is the number of samples.

Although a time-consuming calculation when done by hand, determining the standard deviation is an automated component of all spreadsheets and many calculators.

Fig A1.4 Normal distribution curve



The most common shape of curve found in manufacturing processes is the bell-shaped curve which has a normal (also referred to as Gaussian) distribution. This distribution has a statistical relationship between positions on the curve (measured in standard deviations) and the number of values lying inside and outside that position. For example, in a normal distribution, 99.7% of all measured values lie within three standard deviations of the mean (see Fig A1.4).

The standard deviation can then be used to quantify process capability in terms of the number of outputs which lie inside or outside the specification (see opposite).

The importance of sample size

You will obtain meaningful results only if you take sufficient measurements. If you calculated the range and standard deviation for a sample of four, the results would tell you very little of value. However, measurements take time and cost money, and companies are reluctant to gather thousands of readings to obtain precise results.

In most practical applications, a sample of about 30 measurements is sufficient to give a useful indication of variability. The textbooks referenced in Section 9 give more detailed information about the relationship between sample size and population.

Fortunately, the theory of statistics can help to take account of small sample sizes, particularly for on-going monitoring of processes, and a series of constants has been derived for this purpose (see Appendix 2).

Defining capability

Industrial companies usually have set target specifications (or *tolerances*) for the key attributes of their products, ie they specify the highest and lowest values that are acceptable. The *capability* of a process is a measure of how well it can meet the specification set. It indicates the percentage of products likely to be rejected for being outside the specification. The more variable a process is, the less capable it will be. A *capable* process is one that can meet the end-use specification most of the time.

For example, a doorway 1 950 mm high is quite *capable* in terms of allowing the population to pass through it without stooping, provided that population is distributed normally - ie the causes of variation are normal. If the population sample has an average height of 1 740 mm and a standard deviation of 73 mm, then the doorway is 210 mm (2.875 standard deviations) above that average. Statistical tables predict that 99.87% of the population will have a height below 1 950 mm, so only slightly more than one person in 1 000 will have to stoop to pass through the doorway.

If a substantial number of people then start hitting their head when passing through the doorway, this is a signal that something has changed. That change could be either in the height of the doorway (eg the lintel has slumped) or in the population passing through (eg an influx of international rugby players). In industry terms, the first of these changes is equivalent to a change in the process equipment, while the second is equivalent to a change in the materials being processed. In statistical terms, these represent *special* or *assignable* causes of variation.

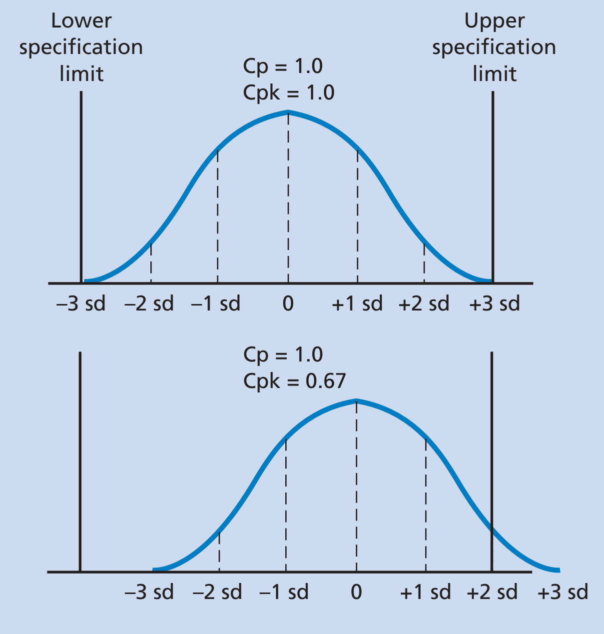
Quantifying process capability

Process capability can be quantified using two simple calculated measures, Cp and Cpk. These measures compare the process variation (as indicated by the standard deviation) with the specification limits or tolerance.

Cp compares the size of the process variation with the size of the tolerance (the difference between the upper and lower limits of the specification). The smaller the variation in comparison to the tolerance, the larger the value of Cp. However, Cp does not indicate the position of the distribution, ie whether the mean lies centrally between the limits, slightly to one side, or outside the limits. Cp is, therefore, sometimes referred to as the 'theoretical' capability - it tells you how well the process would meet the specification *if* it was correctly centred.

Cpk measures capability in a similar way to Cp and also takes account of the position of the sample mean in relation to the specification limits, ie it measures how well the process is centred within the specification limits.

Fig A1.5 Process capability measures



Cp, therefore, indicates the spread of the process and Cpk indicates both its spread and position. This is shown graphically in Fig A1.5.

With the distribution mean centred between the upper and lower specification limits (upper graph of Fig A1.5), Cp and Cpk both indicate the spread of the process. When the distribution mean moves off-centre (lower graph), this is indicated by a reduction in Cpk while Cp stays the same. Had the spread also changed, this would have changed both Cp and Cpk. Calculating and comparing Cp and Cpk allows you to identify the extent to which the process is both theoretically capable and centrally positioned.

To carry out a process capability study you need to run the process over a reasonable period of time without making any adjustments, and then measure the quality parameter(s) in your specification. If you make adjustments you introduce a special cause or variation. What you are trying to determine in a capability study is which common and, possibly, special causes are influencing normal production. Ideally, at least 30 measurements are needed to give statistically valid results.

Calculating Cp

To determine Cp:

1. Calculate the *tolerance* of the specification (ie the difference between the maximum and minimum permitted values).
2. Calculate the *standard deviation* of the process from the process measurements.

3. Divide the tolerance by six times the standard deviation of the process, ie

$$Cp = \frac{\text{specification tolerance}}{\text{Standard deviation} \times 6}$$

A Cp of 1.0 means that the process is theoretically 'capable', ie the tolerance of the specification equals six times the process standard deviation.

If the process is correctly centred (ie it has been set up so that the mean value of the process equals the centre of the specification), the tolerance limits (the maximum and minimum permitted values) will be located at ± three times the standard deviation on the process's normal distribution curve (see Fig A1.5).

The number of measurements within ± three standard deviations of the mean on a normal distribution curve is 99.7%, with only 0.3% (three measurements in 1 000 or 3 000 measurements in a million) lying outside three standard deviations and, therefore, outside the tolerance limits.

In practice, real processes are not centred exactly and it is, therefore, usual to aim for a Cp value of at least 1.3. This provides some leeway, allowing the process to drift a little off-centre while still maintaining low levels of out-of-specification results (companies producing components for the motor industry are usually required to have a process with a Cp of at least 1.3, or to be working and investing to achieve this).

Table A1.1 provides a summary for three different Cp values. In each case, the process is assumed to have a normal distribution and to be correctly centred.

Table A1.1 Expected reject rates for centred processes with a range of Cp values

Cp	Products within specification (%)	Products outside specification (%)	Number of rejects per million
0.67	95.4	4.6	46 000
1.00	99.7	0.3	3 000
1.33	99.994	0.006	60

A process with a Cp of 1.33 has permitted tolerances of ± four standard deviations. In this case, 99.994% of measurements would fall within the tolerance levels, with 0.006% or 60 measurements per million lying outside that range.

A process with a Cp of 0.67 has permitted tolerances of ± two standard deviations. In this case, 95.4% of measurements would fall within the tolerance levels, with 4.6% or 46 000 measurements per million lying outside that range.

Calculating Cpk

To calculate Cpk:

1. Calculate the process's mean and standard deviation from the process measurements.
2. Subtract the measured *mean* value from the permitted *maximum* in the specification (D1).
3. Subtract the permitted *minimum* value in the specification from the measured *mean* value (D2).
4. Choose the smaller of these two numbers, and divide it by three standard deviations, ie

$$Cpk = \frac{\text{the smaller of D1 and D2}}{\text{Standard deviation} \times 3}$$

In the case of industrial measurements, the Cpk value will usually be smaller than the Cp value, reflecting the effect of poor centring. As in the case of Cp values, a Cpk of 1.3 or above is usually taken as a sign that a process is performing well with some leeway for drift.

A decreasing Cpk value is a good indicator that *special* causes of variation are creeping in, eg changes in process equipment or materials.

One of the purposes of statistical process control charts (see Section 8 and Appendix 2) is to detect this happening.

Process control charts

The principles

Simple process control charts are a useful means of providing information about process change. They indicate when the variability of your process is the result of *normal* causes of variation (which should be ignored) and when they are the result of *special* causes of variation that you should do something about. The chart might, for instance, indicate that the process is going from an 'in control' state to an 'out of control' state. Alternatively, it might show a developing trend such as a change in the mean or the range for the process.

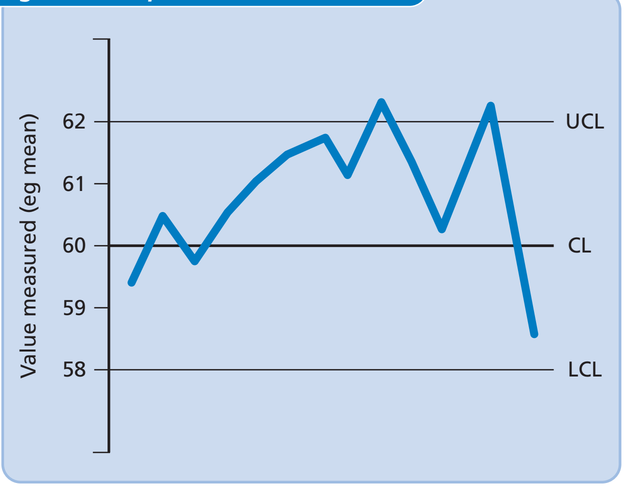
Measuring the performance of the process in this way will give an early indication of possible problems that could cause more 'damage' downstream. It is more cost-effective to identify a problem in a component at an early processing stage, rather than when that component has been incorporated into a larger product or, worse still, sold to a customer who then becomes dissatisfied with the product.

Furthermore, using a quantitative measure allows the cost implications of any proposed changes to be calculated. Investment in improvements can thus be justified.

Control charts are very simple to use. Once your process is operating at the required level of capability:

1. Take a significant number of measurements and calculate the initial mean value of the process (shown by subscript zero, eg x_0, R_0).
2. Use simple equations to calculate an Upper Control Limit (UCL), a Lower Control Limit (LCL) and a Centre Line (CL). These equations and their associated coefficients are described below.
3. Draw on a chart the three horizontal lines that correspond to the LCL, CL and UCL values.
4. Regularly measure and plot process performance on the chart.

Fig A2.1 Simple control chart



If the measured value stays well within the two boundary lines (UCL and LCL), your process is under control and you need not take any action.

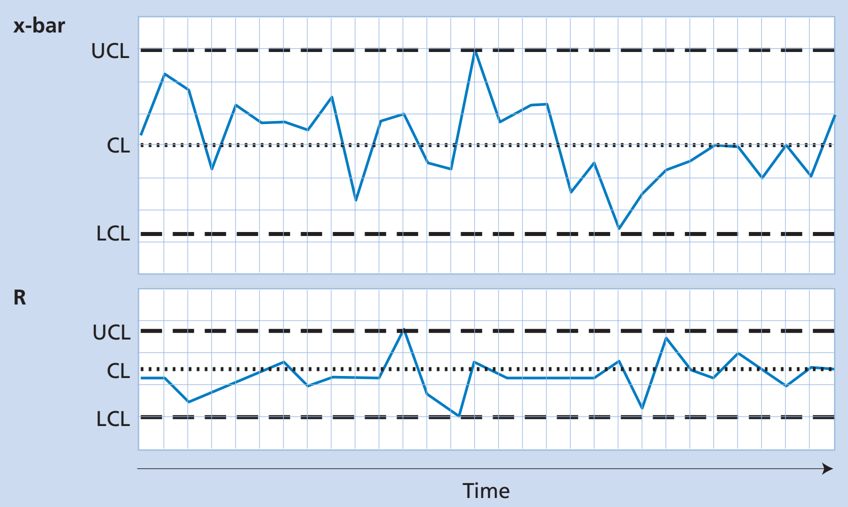
If the measured value moves outside the boundaries, your process needs checking and correcting if necessary.

If the measured value gradually moves away from CL towards one of the limits, this may indicate that your process needs attention.

The 'x-bar R' chart (mean and range)

One of the most common types of control chart is the 'x-bar R' chart, which records both the mean (x-bar) and range (R) of measurements. This is developed from measurements of a particular characteristic of the product, such as machined diameter. These measurements are taken from sets of sequential samples taken at regular intervals, with each set containing the same number of samples. For example, you could measure the first five samples produced on the hour and then make measurements every two hours. For each sampling event, the measurements are used to calculate the mean and the range, which are plotted on the x-bar R chart. An example of an x-bar R chart is shown in Fig A2.2

Fig A2.2 A typical x-bar R chart



The upper graph shows the mean for each sample set over time. The lower graph, which uses the same x axis (time) shows the range (ie the difference between the highest and the lowest). In order to develop the criteria against which the variation can be judged, control limits must be calculated. These are shown in Fig A2.2 as dotted lines.

To determine the control limits for an x-bar R chart, you should take a number of sample sets from the process whilst running at your desired level of capability. Usually around 20 sets provide sufficient accuracy.

The x-bar CL is the mean of all the samples in all the sample sets whilst running at your desired level of capability (also referred to as x_0).

The range CL is the mean range of all sample sets whilst running at your desired level of capability (also referred to as R_0).

The UCL and LCL indicate how much variation there would be if only common causes of variation were present. They are calculated from x_0, R_0 and constants which depend on the number of samples in each sample set:

UCL (mean) = $x_0 + A_2 R_0$
LCL (mean) = $x_0 - A_2 R_0$
UCL (range) = $D_4 R_0$
LCL (range) = $D_3 R_0$

The constants A_2, D_3 and D_4 depend on the number of samples in the sample set, with those for set sizes 2 to 10 shown in Table A2.1 (see page 41).

Interpreting the x-bar R chart

One of the main benefits of statistical process control is its ability to indicate the onset of a problem at an early stage and provide information to help identify the cause, thereby enabling speedy rectification. The x-bar R chart provides a simple, visual way of detecting special causes of variation.

If only common causes of variation are present, the sample set 'means and ranges' will concentrate around the CL and thin-out towards the UCL and the LCL. In fact, if the process has a normal distribution curve, only 0.3% of the points would be expected to cross the UCL and LCL. The presence of one or more points beyond either control limit strongly indicates an out-of-control situation, and the presence of a special cause of variation.

Furthermore, when under control, the distribution of the means and ranges each side of the CL would be random; there would be no discernible trend. If the chart does show a trend, even if all points are within the control limits, there is probably a special cause of variation present. You can apply rules to these to help identify whether a trend really exists, and many computer-based programs can automatically highlight any such instances for you. A commonly used rule is that seven consecutive points falling on the same side of the CL indicates a trend caused by a special cause. Another rule is that two out of three consecutive points greater than 0.67 of the difference between the CL and either control limit, indicates a special cause.

When the existence of a special cause is indicated, use the control chart to help identify it as follows:

- Identify the likely start time of the cause by looking for the start of the trend.
- Compare the likely start time with activities on the production line (batch changes, shift changes, maintenance work etc).
- Compare the x-bar and range halves of the chart to identify whether it is just the mean which has moved (a potential calibration error on the equipment or material) or whether the range has increased as well. If needed, a repeat check of Cp and Cpk will give a more accurate indication of this.
- Compare the chart information with that of charts on other lines in the same area, or those recording general variables (eg temperature).

Sample size and coefficients

While larger samples will always provide a more accurate analysis and a more rapid feedback for process control purposes, there are usually practical limits on the number of measurements that you can sensibly take for each production sample. These limits are determined by the time and cost involved.

The one-off initial investigations into variability discussed earlier in this Guide used samples of more than 30 measurements. This is not usually practical where routine measurements are being taken for process control purposes. In practice, industrial companies with processes operating in control at a reasonable level of capability can take samples with as few as two measurements. They rarely justify samples of more than ten measurements. However, there are exceptions, notably in industries that use natural (and thus highly variable) raw materials.

Despite the small number of samples usually taken, statistical process control can be used successfully even in areas such as leather-making, biscuit production, pizza manufacture etc. There are two important points to remember:

- Where samples are very small, it is not usually worth calculating the standard deviation. Common practice is, therefore, to calculate the range (maximum – minimum values) and to convert this to a notional standard deviation value using constants such as those shown in Table A2.1.
- The rule of thumb when dealing with small numbers of discrete events (eg product rejects) is to do nothing until certain.

Coefficients

Control chart limits should really be based on the standard deviation of the characteristic being measured. However, as indicated previously, range is often used as a much more convenient measure of variability, especially with low sample size. Table A2.1 shows constants derived by statisticians for the calculation of control limits from range values. Sample sizes are from two to ten.

Table A2.1 Control chart coefficients for values of n of up to 10

n	A_2	D_3	D_4
2	1.880	*	3.267
3	1.023	*	2.575
4	0.729	*	2.282
5	0.577	*	2.115
6	0.483	*	2.004
7	0.419	0.076	1.924
8	0.373	0.136	1.864
9	0.337	0.184	1.816
10	0.308	0.223	1.777

* The value of D_3 is not considered for a sample of <7, and the lower limit for the range is effectively zero.

Types of process control chart

There are several types of process control chart, each plotting slightly different variables and each using different statistical rules to calculate the LCL, CL and UCL values. They take into account factors such as skewness in a distribution and the effects of sample size.

You can easily select the type of chart you need to use by looking at the headings in each case. You do not need to understand details of the statistical theory underlying the different types.

Charts used where product properties involve fractional values

Two types of chart are used where the parameters measured are continuous - length, weight, concentration etc: the x-bar R chart and the moving average and range chart.

x-bar R chart

Used where several measurements (ie several values of x) are taken at each sampling time.

The chart has two components:

- the x-bar component, which plots the average value of each sample of n measurements (ie all the measurements taken at any one time);
- the R component, which plots the range of the sample (maximum value – minimum value).

Control limits for x-bar chart

UCL = $x_0 + A_2 R_0$
CL = x_0
LCL = $x_0 - A_2 R_0$

Control limits for R chart

UCL = $D_4 R_0$
CL = R_0
LCL = $D_3 R_0$

where x_0 and R_0 are mean values of the process and where A_2, D_3 and D_4 are coefficients associated with each value of n (see Table A2.1).

Moving average and range chart

Used where only a single measurement of x can be taken at each sampling time.

Moving averages and ranges are plotted over 'n' readings.

The moving average is derived as follows:

$$\frac{\text{Current reading + previous n-1 readings}}{n}$$

The moving range is derived as the maximum value of the current and previous n-1 readings, minus the minimum value for the same set of readings.

Control limits

The control limits for the moving average and the moving range are calculated in the same way as for the x-bar R chart, with coefficients for a sample of 'n' measurements (see Table A2.1).

The use of these charts is illustrated in Section 8.2 (Fig 11) and opposite *The use of moving average and range charts.*

Charts used where the parameters are discrete values or whole units

pn chart

Used where the sample size (n) is constant.

The number of rejects (for example) is plotted and equals the fraction of rejects (p) multiplied by the sample size (n).

Control limits

$$UCL = p_0 n_0 + 3\sqrt{p_0 n_0 (1 - p_0)}$$
$$CL = p_0 n_0$$
$$LCL = p_0 n_0 - 3\sqrt{p_0 n_0 (1 - p_0)}$$

where p_0 and n_0 are the mean values of the process.

p chart

Used where the sample size (n) is variable.

The fraction of rejects (p) is plotted for each sample.

Control limits

$$UCL = p_0 + 3\sqrt{p_0 (1 - p_0)/n_0}$$
$$CL = p_0$$
$$LCL = p_0 - 3\sqrt{p_0 (1 - p_0)/n_0}$$

where p_0 and n_0 are the mean values of the process.

The use of a p chart is illustrated on page 45 *The use of p charts*.

Charts used to control the number of defects in a part or unit

Two types of chart can be used to control, for instance, the number of defects within a part or unit (eg surface defects, defective joints in wiring, texture defects, holes), where the parameters measured are discrete values: the c chart and the u chart.

c chart

Used where the sample selected is one single item of constant size (eg a bench-top or a batch of five bench-tops).

The concentration of defects per item (c) is plotted.

Control limits

UCL = $c_0 + 3\sqrt{c_0}$
CL = c_0
LCL = $c_0 - 3\sqrt{c_0}$

where c_0 is the mean value of the process.

u chart

Used where each sample represents:

- more than one unit of measurement, eg unit area for products of variable size such as hides of leather;
- more than one item (where a low defect rate means that a sample of more than one item is needed).

The concentration of defects per unit area, volume, item etc (u) is plotted.

Control limits

UCL = $u_0 + 3\sqrt{u_0/n_0}$
CL = u_0
LCL = $u_0 - 3\sqrt{u_0/n_0}$

where u_0 and n_0 are the mean values of the process.

The use of a c chart is illustrated in Section 8.3.

The use of moving average and range charts

Section 8.2 of this Guide shows how x-bar R process control charts were introduced to maintain control of the leg support machining process. Moving average and range charts could also be of value in this situation. A moving average and range chart uses single measurements taken at regular intervals and plots the averages and range over a fixed number (n) of previous measurements.

In this example, the Green and Keen Production Director opted for one measurement each day and plotted the result of the previous five days (a one-week moving average). This provided useful back-up to the x-bar R chart, particularly during production periods when everyone is working to capacity to meet 'panic' orders from customers and when multiple sampling could become a casualty of pressure of work.

The main advantages of this type of chart are:

- only one measurement is required each day;
- 'smoothing' the data makes it easier to identify long-term trends.

Its main disadvantages are:

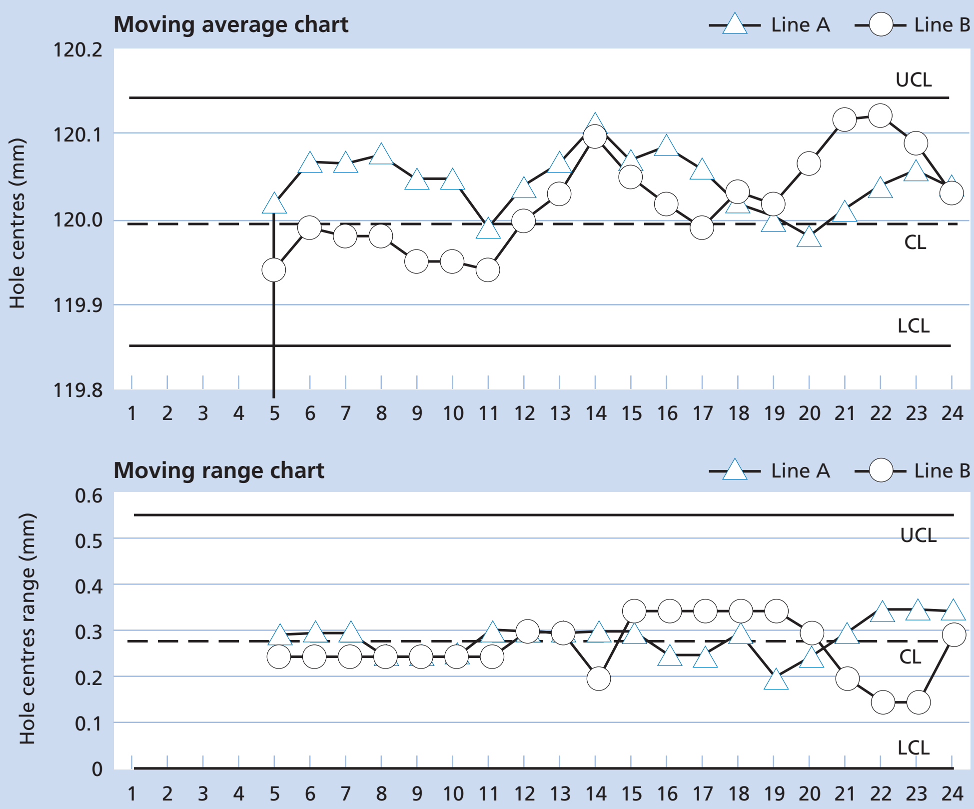
- measurements must be taken for at least five days before any trend can be confirmed;
- forgetting to take a measurement on any one day would make the next five plots invalid;
- averaging over a five-day period will hide any repeated variation within the week.

The moving average and moving range values are calculated as shown on page 42. Table A2.2 overleaf uses the capability study measurements after remedial engineering work as if they had been recorded on successive working days. The moving average and moving range values can then be plotted on a control chart (beginning on day 5). Fig A2.3 overleaf shows the data from Table A2.2 plotted in this way.

Table A2.2 Moving averages and moving range (n = 5)

	Raw data		Moving average		Moving range	
	Line A	Line B	Line A	Line B	Line A	Line B
1	119.95	119.85				
2	119.95	119.90				
3	119.90	119.85				
4	120.10	120.00				
5	120.20	120.10	120.02	119.94	0.30	0.25
6	120.20	120.10	120.07	119.99	0.30	0.25
7	119.95	119.85	120.07	119.98	0.30	0.25
8	119.95	119.85	120.08	119.98	0.25	0.25
9	119.95	119.85	120.05	119.95	0.25	0.25
10	120.20	120.10	120.05	119.95	0.25	0.25
11	119.90	120.05	119.99	119.94	0.30	0.25
12	120.20	120.15	120.04	120.00	0.30	0.30
13	120.10	120.00	120.07	120.03	0.30	0.30
14	120.20	120.20	120.12	120.10	0.30	0.20
15	119.95	119.85	120.07	120.05	0.30	0.35
16	120.00	119.90	120.09	120.02	0.25	0.35
17	120.05	120.00	120.06	119.99	0.25	0.35
18	119.90	120.20	120.02	120.03	0.30	0.35
19	120.10	120.15	120.00	120.02	0.20	0.35
20	119.85	120.10	119.98	120.07	0.25	0.30
21	120.15	120.15	120.01	120.12	0.30	0.20
22	120.20	120.05	120.04	120.13	0.35	0.15
23	120.00	120.00	120.06	120.09	0.35	0.15
24	120.00	119.85	120.04	120.03	0.35	0.30

Fig A2.3 Moving average and moving range charts based on Table A2.2



The upper and lower control limits and the centre line of the chart were derived as follows, using the chart equations shown on page 41.

Limits for the moving average are:

$$UCL = x_0 + A_2 R_0$$
$$= 120 + (0.577 \times 0.27)$$
$$= 120.16$$

$$CL = x_0$$
$$= 120.00$$

$$LCL = x_0 - A_2 R_0$$
$$= 120 - (0.577 \times 0.27)$$
$$= 119.84$$

Limits for the moving range are:

$$UCL = D_4 R_0$$
$$= 2.115 \times 0.27$$
$$= 0.57$$

$$CL = R_0$$
$$= 0.27$$

$$LCL = D_3 R_0$$
$$= \text{zero}$$

In this example, the value for x_0 was set to the target value for hole centre spacing (120 mm).

To plot both Line A and Line B on the same chart, the mean range values are derived for each line from the 20 moving range values, and the lower value (0.27) is selected as R_0.

From Table A2.1, for a sample size of 5, $A_2 = 0.577$ and $D_4 = 2.115$. D_3 is not defined.

Analysis of Fig A2.3 shows that the moving average and range chart is staying in control, confirming the x-bar R chart. Comparison of Lines A and B on the moving average chart shows a similarity in the curves between days 5 and 15. This might be a coincidence, but could equally point to a special cause of variation such as temperature variation in the machining shop. A repeat of this type of pattern would be worth investigating.

The use of p charts

Section 7.1 of this Guide identified engineering work that was carried out to improve the machining of leg supports and thereby prevent bench-top rejects during assembly. In this situation it is important:

- to check that an improvement in the level of rejects has actually taken place;
- to ensure that the improvement is maintained and that no new factors have been introduced to cause products to be rejected.

Both have implications for a company's bottom line since rejection at the assembly stage usually involves scrapping the component (the bench-top in the Green and Keen example) and the work that has already taken place to prepare it for assembly (lamination in the Green and Keen example).

Some form of on-going recording and assessment of rejection levels is, therefore, important. One possible option is to use a p or a pn chart, as indicated on page 42, for situations where the rejects and the total number of items produced are discrete variables with whole number values.

When applying these charts to the Green and Keen example, p represents the proportion or fraction of the assembled bench-tops that have to be rejected each day because of problems such as leg support fit, laminating defects and other gross defects.

Two key measures were required to construct a p or a pn chart - the total number of bench-tops produced each day (n_p) and the number of bench-tops rejected each day (n_r). Records were kept at Green and Keen for both measures over a four-week period (Table A2.3). These showed that:

- the number of bench-tops assembled in one day can vary;
- the number of bench-top rejects over the four-week period averaged just over one per week (ie considerably less than one per day).

Table A2.3 Total production and rejects at the assembly stage

	Date	Production per day	No of rejects
	04 Jan	40	
	05 Jan	50	
	06 Jan	53	
	07 Jan	47	1
	08 Jan	45	
Week 1 Total		*235*	*1*
	11 Jan	42	
	12 Jan	50	1
	13 Jan	49	
	14 Jan	53	2
	15 Jan	46	
Week 2 Total		*240*	*3*
	18 Jan	47	
	19 Jan	47	1
	20 Jan	51	
	21 Jan	49	
	22 Jan	43	
Week 3 Total		*237*	*1*
	25 Jan	45	
	26 Jan	47	
	27 Jan	52	
	28 Jan	50	
	29 Jan	46	1
Week 4 Total		*240*	*1*
OVERALL TOTAL		**952**	**6**

Reference to page 42 indicates that the p chart is the most appropriate type of control chart for a situation in which the sample (number of bench-tops assembled in a given period) is not of a constant size.

With regard to the rejection rate, had one or more rejections occurred each day, it would have been possible to derive p using the equation:

$$p = \frac{n_r}{n_p} \times 100 \text{ (as a percentage).}$$

However, in this example it was more appropriate to derive values for p on a weekly basis as follows:

$$\frac{\text{Sum of } n_r \text{ values Monday-Friday}}{\text{Sum of } n_p \text{ values Monday-Friday}} \times 100$$

The calculated weekly percentage rate for bench-top rejection is shown in Table A2.4. The average weekly percentage rejection rate for the four-week period (p_0) is 0.63% and is derived from a total of six rejects and 952 units produced during that time. Average weekly production for the same period (n_0) is 238 bench-tops. These values for p_0 and n_0, when applied to the equations given on page 42, give the following upper and lower control limits and centre line for the chart:

$$\begin{aligned}\text{UCL} &= p_0 + 3\sqrt{p_0(1-p_0)/n_0}\\ &= 0.0063 + 3\sqrt{(0.0063(1-0.0063)/238)}\\ &= 0.0217\end{aligned}$$

$$\text{CL} = 0.0063$$

$$\begin{aligned}\text{LCL} &= p_0 - 3\sqrt{p_0(1-p_0)/n_0}\\ &= 0.0063 - 3\sqrt{(0.0063(1-0.0063)/238)}\\ &= -0.0091\end{aligned}$$

LCL is corrected to zero as a negative value is physically meaningless.

Table A2.4 Rate of bench-top rejection during a four-week period

Week	Total production	Total no of rejects	Rejects as fraction of total production	Rejects as % of total production
1	235	1	0.0043	0.43
2	240	3	0.0125	1.25
3	237	1	0.0042	0.42
4	240	1	0.0042	0.42
Total	**952**	**6**		
Average per week	**238**	**1.5**	**0.0063**	**0.63**

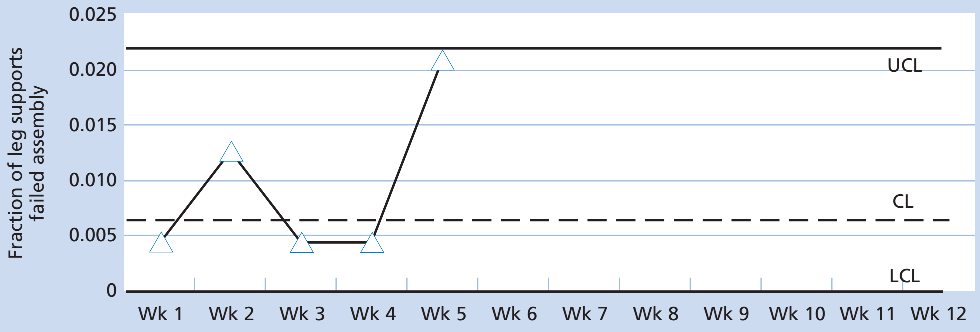
The control chart shown in Fig A2.4 overleaf is based on Table A2.5. This shows values from the first four weeks plus an additional value for Week 5. The value for Week 5 is very close to the upper control limit and should be taken as a *warning* that something may be changing for the worse. The value does **not** indicate 'panic stations': statistics show that, for the samples selected, there is a chance of about one in 20 that a value of the order of Week 5 will occur at random, even when the process is under control. However, it would be important to make a careful check of the value for Week 6[2].

[2] Several of the books recommended in Section 9 deal in more detail with the interpretation of data of this type.

Table A2.5 Weekly records for control chart construction

Week	Output	Rejects	Fraction	LCL	UCL
1	235	1	0.0043	0	0.0217
2	240	3	0.0125	0	0.0217
3	237	1	0.0042	0	0.0217
4	240	1	0.0042	0	0.0217
5	241	5	0.0207	0	0.0217
6				0	0.0217
7				0	0.0217
8				0	0.0217
9				0	0.0217
10				0	0.0217
11				0	0.0217
12				0	0.0217

Fig A2.4 A p control chart for rejects at the bench-top assembly stage



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