1. THE CHALLENGE OF USING STATISTICAL TECHNIQUES IN INDUSTRY

In the manufacturing industry, many companies are facing the pressing need to work with greater efficiency and to lower costs. The automotive industry is a leading example of this trend, as it is has been among the most globally distributed and competitive of industries for many decades (the 2008 financial crisis being only the latest challenge for companies). The dominant approach to greater efficiency is the adoption of one of several different process improvement methodologies, such as Six Sigma, lean manufacturing, or ‘lean Six Sigma’ (George et al., 2005; Montgomery & Woodall, 2008; Womack et al., 1991). One of the most widely used techniques in process improvement, and the focus of this paper, is statistical process control (SPC) (Caulcutt, 1995; Oakland, 2003). We look particularly at the use of one-number process measures, which managers and statisticians consider useful for communication and negotiation between managers, engineers and shopfloor operators about the state of processes and the potential for improvement (Kotz & Johnson, 1993).

As mathematics and statistics education researchers we are interested in the case of process improvement because it involves statistical ideas and techniques at its core. Some of these are used across the whole company, so that employees at most levels need to learn several statistical techniques (Pyzdek, 1991). This confronts companies and educators with the question of what their employees need to know about statistics and how they can be trained.

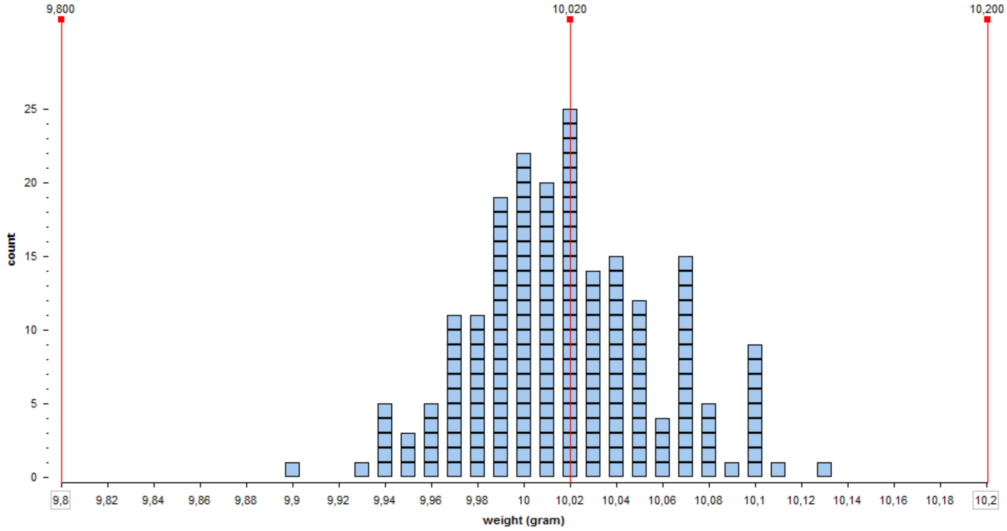


Figure 1: Simulated results of measuring the mass of 200 bolts, each with a target mass of 10 grams, actual mean of 10.02, specification limits of 9.8 and 10.2 g. Standard deviation here is 0.04. Cpk = 1.5, which would be considered very satisfactory as the probability of producing something outside specification is extremely small.

To illustrate this problem we give an example that we have observed and with which we will deal in this paper, drawn from the use of statistical process control (SPC) in an automotive assembly plant. Assume particular bolts produced are expected to weigh 10 grams (target) and should not be below 9.8 or above 10.2 g (specification limits). Ideally the mean of measurements of this characteristic will be close to target and the variation small, as in Figure 1. Cpk, a process capability index, is used in SPC as a measure of how well a key characteristic of items produced (in this case mass) stays within the specification limits. A higher Cpk value (small standard deviation in relation to large distance between mean and both specification limits) is generally better than a low one.

$$C_{pk} = \min(C_{pkl}, C_{pku})$$

where:

$$C_{pku} = \frac{USL - \overline{X}}{3\sigma}, \; C_{pkl} = \frac{\overline{X} - LSL}{3\sigma}$$

and

USL = upper specification limit

LSL = lower specification limit

$\overline{X}$ = mean

σ = standard deviation

The Cpk in Figure 1 is (10.2 – 10.02)/(3 * 0.04) = 1.5, which would be considered very satisfactory in a manufacturing context. Later in the paper we provide more background to this Cpk measure. Our main point here is this: Imagine presenting such a formula to an assembly line operator in his 50s who gained a basic mathematics qualification at the age of 14! Yet this is what the observed training course did. Operators do need to know something about the Cpk number, because the company sets a target minimum value of Cpk for critical processes and operators have to monitor these Cpk's (but calculations are done away from the production area by a specialist SPC department). If the Cpk of their production process is too low, they can be asked to justify it. As one trainer told us, semi-jokingly: "You can be beaten up for a low Cpk."

This example illustrates a tension that arises in companies: employees need to learn about statistical measures that are typically formulated in algebraic symbolism, and hence poorly understood. What kind of training would help first-level managers and shopfloor operators to understand the mathematics of such measures? Their understanding needs to be grounded in an ability to communicate using statistical measures with managers, engineers and suppliers. The role of suppliers is very significant for automotive manufacture as the principle manufacturing company has contracts with tens or even hundreds of specialist manufacturing companies in a 'supply chain'; aside from the car's metal bodywork and core engine parts, most of the thousands of other components in the car are made to specification by suppliers.

The usual formal approaches to teaching statistics do not seem to be adequate for this situation. As evidenced in research on school statistics (e.g., Shaughnessy, 1992), most formal approaches to teaching statistics leave students with brittle formal knowledge and a poor ability to communicate statistical information. In a workplace setting we would expect similar problems.

To get a better sense of the problems with statistical measures in process improvement strategies, this paper first addresses the following question in the context of the automotive industry:

1. What are the problems with statistical process control (SPC) in practice and in training?

In the first research phase, we identified the process capability indices such as Cpk as problematic but essential for improving and communicating process performance.

We then set ourselves the challenge to 're-present' (represent in another way) such indices through statistical software tools (small visual web-based tools, programmed in Flash) such that they could serve as artefacts facilitating workplace communication, including to be used by employees with little formal background in mathematics. Following Bowker and Star (1999) we consider such artefacts that facilitate communication to be 'boundary objects':

> …we define boundary objects as those objects that both inhabit several communities of practice *and* satisfy the informational requirements of each of them. In working practice, they are objects that are able both to travel across borders and maintain some sort of constant identity. They can be tailored to meet the needs of any one community (they are plastic in this sense, or customizable). At the same time, they have common identities across settings. (p. 16, emphasis in the original)

Next, to evaluate the extent to which our design and collaboration with company trainers was successful, and to learn lessons for future design-based projects, this paper continues to address two further research questions:

2. What are the characteristics of the design process that seem crucial for these computer tools to become boundary objects?
3. Do the new software tools function as boundary objects in the workplace, i.e. do they indeed facilitate communication between different communities?

We will answer the second question by analysing our collaboration with workplace trainers, and the third question by analysing the trajectory from the creation of the visual and dynamic statistical software tools to how they were eventually used in the collaborating companies and beyond. We illustrate this 'boundary object trajectory' (cf. Lallimo et al., 2007) from our interaction with the trainers (stage 1 in Figure 2), with an early version of the tools, to the tools being used during training courses, first by ourselves (stage 2) and next by trainers (stage 3) without our involvement. Then, we show how the tool helped an employee to communicate with a supplier (stage 4), and finally summarise the further independent life of the tools in other factories (stage 5) beyond this research project.

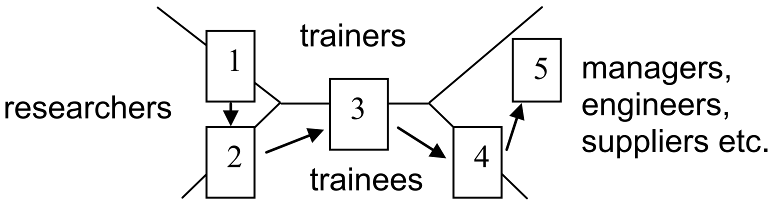


Figure 2: Boundary object trajectory. The lines represent boundaries between different communities and the boxes represent the computer tools at those boundaries.

2. BOUNDARY OBJECTS, TECHNOLOGY-ENHANCED BOUNDARY OBJECTS AND DESIGN PRINCIPLES

A number of theoretical perspectives have been used to examine the complex interactions within organisations, for example: communities of practice (Wenger, 1998), social worlds and articulation work (Strauss, 1993), and activity theory (Engeström, 2001). All these perspectives share the viewpoint that a basic requirement for the sub-communities in an organisation is to collaborate towards common goals whilst having different motives, tools, and rules, and also different types of knowledge. For example, in automotive manufacturing, managers, shift leaders (i.e., operator team managers), operators and engineers are all concerned with producing first-quality cars, but have very different roles in the overall process and have varying knowledge of it.

To study communication in such complex settings many workplace researchers have drawn on the original work of Star and Griesemer (1989) on boundary objects (Lee, 2007, provides a useful overview). Star and Griesemer described an example of how professional biologists found ways to communicate with amateur naturalists so that both communities could gain from their different practices which previously often led to conflicts of interest. The key to this realignment of interests was the introduction of a specially designed record document as a boundary object which managed the sharing of information. Star and Griesemer wrote that: “the creation and management of boundary objects is a key process in developing and maintaining coherence across intersecting social worlds.” (p. 393). In subsequent research, many artefacts have been described and analysed as boundary objects in workplace situations, for example: classifications, scientific categories and standards (Bowker & Star, 1999); cause maps, narrative maps, models, schemes (Boland & Tenkasi, 1995); medical claim forms processed through the different departments of an insurance company (Wenger, 1998).

In our own workplace research, we have looked at the roles of artefacts which involve symbolic representations of the mathematical relationships inherent in workplace processes. We found that such artefacts were often intended to communicate between different communities, such as operators, middle and senior managers, and process engineers (Bakker et al., 2006; Noss et al., 2007). We investigated in detail how these artefacts did or did not function as communicative, and how this suggested underlying skills problems (Hoyles et al., 2007; Kent et al., 2007). This focus, and our desire to enhance as well as understand the statistical knowledge required at work, led us to take the notion of a boundary object as an orienting concept.

As we will illustrate in this paper, standard algebraic representations fail this communicative requirement for many ‘intermediate level’ employees. That is, employees who do not have a university-level education but whose job role requires interpreting and communicating complex technical information, expressed through mathematics; first-level managers on the shopfloor, who manage teams of operators, are a typical case. In factories where SPC is deployed the need to engage with technical information is increased for all employees, but especially for the intermediate level where educational background is often basic and employees have achieved promotion through effort and self-improvement.

Our view was that there was a need to alternatively represent statistical knowledge so it could be engaged with by employees from different communities. Our approach to this problem has been to adapt and re-configure one or more existing artefacts from the workplace, using computer software, to produce what we call a *technology-enhanced boundary object (TEBO)*. In our view, the literature on boundary objects pays little attention to disciplinary knowledge although differences in such knowledge hinder communication between communities. Part of our research agenda is therefore to bring this epistemological focus to the discussion of boundary objects and contribute to a pedagogy of creating boundary objects in educational and vocational settings. (See Hoyles et al., in press, for an overview of the range of research we have undertaken.)

In designing TEBOs we have deployed three main design principles. First we identified symbolic artefacts that were intended to be boundary objects in the workplace. Next we re-presented them appropriately so they could assist us in revealing the underlying statistical models on which they were based. Hence *design principle 1* is: re-present artefacts familiar to employees in order to allow employees to engage with relevant statistical structures. In the case we consider here, the artefacts were statistical charts containing the graphical and numerical information used to calculate process measures.

We adopt a constructionist approach (Harel & Papert, 1991) to the learning opportunities, which involves participants building and manipulating computational representations of mathematical and statistical ideas, and requiring them to express their own ideas through the use of appropriate tools. In doing so we open windows onto their thinking and reasoning (Noss & Hoyles, 1996). *Design principle 2* can be summarised thus: using software tools in ways that require participants simultaneously to construct or reconfigure symbolic artefacts and negotiate the meanings around them, and to map these back onto familiar ground.

A *third design principle* is to co-design with experts from the communities at stake. Without their knowledge of the workplace’s contingencies we assumed the tools would have little communicative potential. Successful use of TEBOs is demonstrated by trainers’ continued use of these in their courses, trainers’ demonstration and sharing of TEBOs with colleagues, trainees’ positive feedback, and the use of TEBOs by communities that we have never engaged with.

3. RESEARCH METHODS

3.1 Research Phase 1: Ethnography

To answer the first research question we had to analyse the problems related to using SPC on the shopfloor, involving intermediate level employees. For this we used applied ethnography (Chambers, 2000), meaning we did not immerse ourselves in one company for weeks or months, but visited different companies for several days, all of which were dedicated to *looking for* examples of SPC use rather than *looking at* the workplace with no specific theory or hypothesis. What we learnt in this research phase formed the basis for collaboration on improving existing SPC training; in particular the design of the TEBOs. The companies involved with the ethnography were in the automotive, pharmaceuticals and packaging manufacturing sectors; subsequent phases of the research took place only in the automotive sector initially, and most substantially, with a single company, which we call (pseudonymously) Classic Motors, a UK assembly plant of a car brand owned by a global, multinational parent company.

Our data collection in this car company during the first phase included audio recordings of interviews, field notes, evaluations of several SPC courses and the gathering of workplace artefacts such as SPC charts. Having previously seen process improvement and SPC in use in other companies (Bakker et al., 2006; Hoyles et al., 2007), our ethnographic observations at Classic Motors focused on developing a detailed picture of the intended use and actual function of SPC in the company. As part of the data collection in this phase we:

- interviewed a high-level manager in charge of process improvement to investigate how process improvement techniques were actually used and the shopfloor employees were trained, and to identify problems with implementation;
- interviewed SPC experts and their managers as well as shopfloor employees for explanations of the control charts used in their work;
- attended and evaluated their SPC training course with twenty trainees; the evaluation included a questionnaire, post-survey, of the trainees' experiences and subsequent one-hour interviews with three trainees.

The answer to the first research question was based on our collective analysis of interview transcripts, our own observations and course evaluations. The interviews were especially useful in identifying partially incorrect knowledge of statistical ideas. Findings were discussed with workplace trainers as well as managers and were found to resonate with their own experiences.

3.2 Research Phase 2: Educational Design Research

The data used to answer the second and third research questions stem from the next phase of our research, in which we collaborated with three SPC trainers on the development of *learning opportunities* (computer tools and accompanying learning activities). This phase involved educational design research (Bakker, 2004; Van den Akker et al., 2006). The key idea of design research is to iteratively design learning environments while developing an instructional theory of how to support the learning aimed for. It typically involves several cycles of designing a teaching experiment and analysis leading to revision of both instructional materials and their accompanying instructional theory. We use the term ‘learning opportunities’ to stress that they were intended to be flexible resources for statistical learning that could support employees in developing the statistical knowledge required in their work, and which could eventually be incorporated within, or be presented alongside, other workplace technical training materials.

Our learning opportunities were used as part of three different training courses. These involved a range of employees, from apprentices and assembly line operators to managers and senior professional engineers. In the first course, we used the learning opportunities with seven participants as part of the existing SPC course for about 1.5 hours. In the second course, we had 2.5 hours with seven apprentices and three maintenance engineers. In both cases, Peter (one of the factory’s SPC specialists) was the trainer, and two of the research team led the training in which computer tools were used. Following the method of educational design research we compared what we conjectured would happen in the courses to what actually happened.

A third course took place in a second factory, part of Sporting Motors (pseudonym). Here, our learning opportunities were slotted for an hour into an existing one-week Six Sigma training course with twenty participants. Our computer tools were used to offer a visual and interactive exploration of the statistical concepts which participants had already worked on with pen-and-paper. This training course was delivered by a Sporting Motors SPC specialist, Phil. Both Peter and Phil are self-improved former assembly line operators (in Peter’s case, with more than 25 years working ‘on the lines’), rather than formally educated graduate engineers.

Throughout the second research phase we also:
- kept track of all versions of the computer tools and of design decisions;
- discussed the tools and learning activities during co-design meetings (face to face, phone, email);
- organised follow-up email interviews and phone calls with trainees;
- collected audio recordings and a screen video capture of one pair’s work with the software tools.

Altogether we spent eighteen researcher days in Classic Motors, four at Sporting Motors, and one at a component supplier company.

Our second question on characteristics of the design process is not easily answered by standard research methods; yet answers to such questions are interesting to designers and educators. We consider it worthwhile, therefore, to speculate on such characteristics and illustrate them with episodes from the co-design stage of the research.

Contrary to what school-oriented researchers might expect, we do not evaluate employees’ *learning* directly but present narratives of *impact* on practice as evidence of the outcomes of learning. Not only are managers more interested in the latter, but determining learning outcomes from workplace research is much more difficult than in the structured and constrained environment of a classroom. The companies we worked with were not willing to allocate time for tests as this had cost implications, and videotaping training sessions was not allowed to protect sensitive information from becoming public.

To answer the third question we summarised the information from several sources. We

- obtained additional feedback about tool use in other sites of Classic Motors (tools were published on the web for registered use by other users);
- videotaped a joint presentation of four SPC trainers at a dissemination meeting held at our university and, subsequently, interviews on the trainers' overall experiences;
- kept a record of where the software tools were presented and used.

The data sources collected helped us trace the development of the computer tools as boundary objects and their trajectory beyond our interventions. Again, the selection of episodes used in this paper and our conclusions are based on analysis of all data sources available. Occasional differences in selection or interpretation were discussed within the research team until consensus was reached.

4. TECHNICAL BACKGROUND ON STATISTICAL PROCESS CONTROL

SPC is one of the oldest and most widely used improvement techniques and was used by all the manufacturing companies we studied. It was found in 13 out of the 16 companies Smith (1999) studied in the American car industry. As mentioned before, deploying SPC requires employees, at most levels, to engage with statistics of variability via data and graphs in ways that are far from trivial. This is true for large companies as well as those which are small and medium-sized (Hewson et al., 1997), for whom employee training may be more challenging to carry out.

4.1 The SPC Chart

The central artefact used in Classic Motors for SPC is the SPC chart – an example is given in Figure 3. This artefact is standardised in the sense that the same format is used in all departments of the company, and it is meant to capture particular types of information that is used by several communities. This implies that it is meant to be a boundary object in the sense defined by Bowker and Star (1999).

The standardised SPC charts in the car company have four elements:

1. The upper left area displays the *individual run chart, control chart* or *Shewhart* chart of (in this case) two measurements per day; Figure 3 represents the 'tox strip distance' in deviation from the target in mm (the tox strip is a piece of rubber around windscreens). 0 is nominal but a slightly low average is accepted since the process is stable and does not cause customer complaints.
2. The lower left area shows the *moving range chart* of part-to-part variation (absolute differences between consecutive points) between items produced.
3. The upper right corner is a *sideways histogram*, which shows the overall distribution of data points in the run chart.

4. The lower right corner (enlarged in Figure 4) entails all the relevant figures such as target value, mean, control limits and other information on Cp and Cpk that is discussed later in this paper.

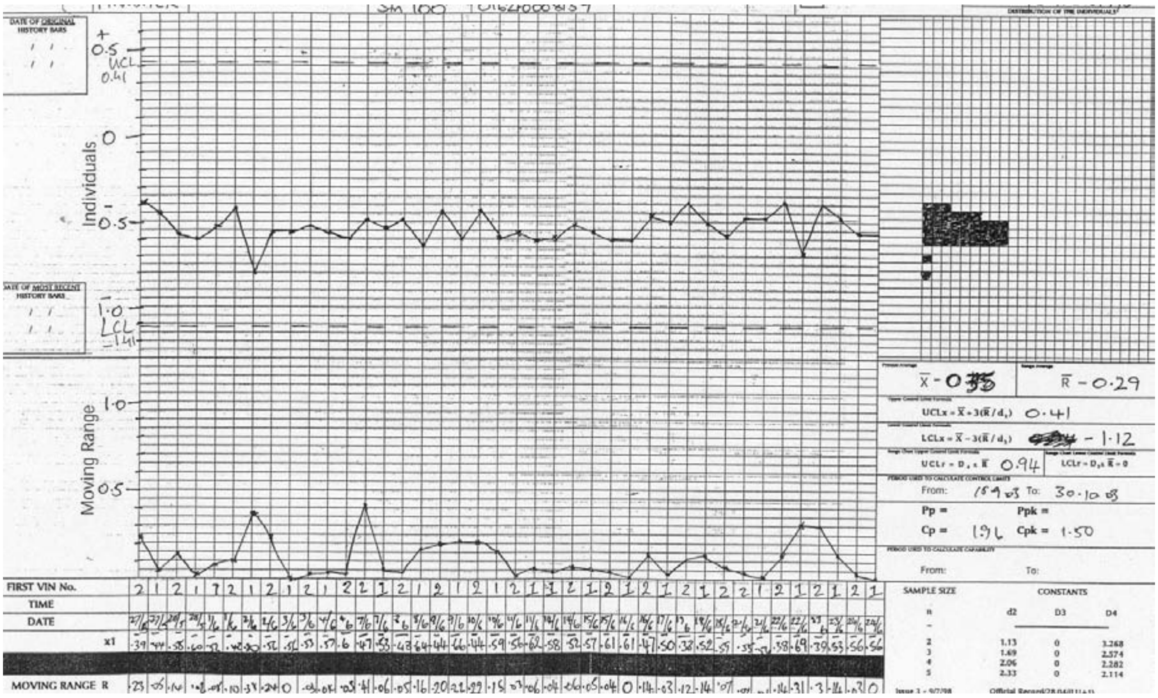
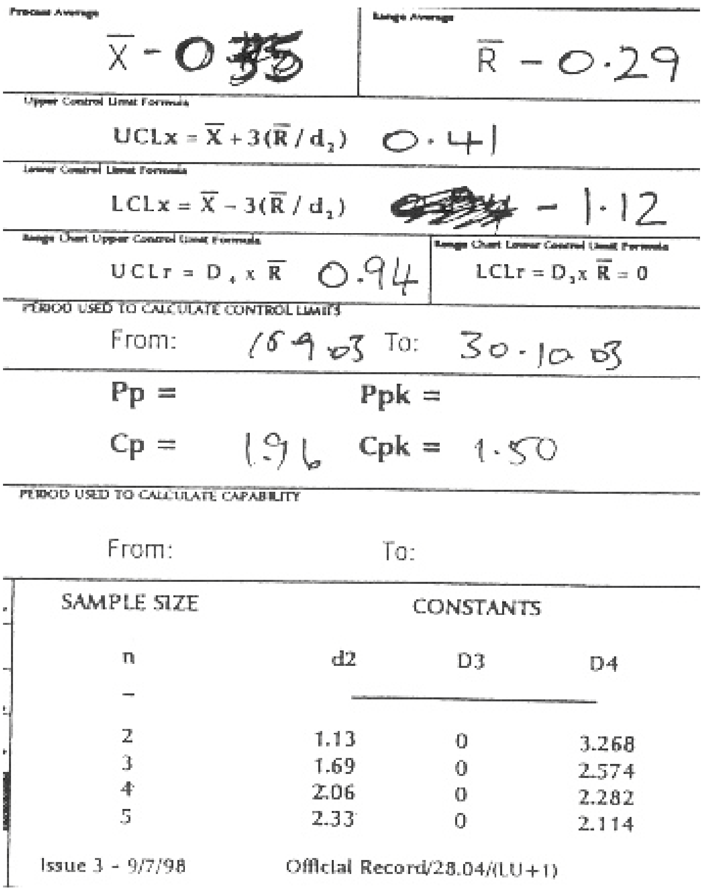


Figure 3: An intended boundary object: an SPC chart from the shopfloor of Classic Motors.



Process Average

$\bar{X}$ - 0 35

Range Average

$\bar{R}$ - 0.29

Upper Control Limit Formula

$UCLx = \bar{X} + 3(\bar{R} / d_2)$ 0.41

Lower Control Limit Formula

$LCLx = \bar{X} - 3(\bar{R} / d_2)$ - 1.12

Range Chart Upper Control Limit Formula

$UCLr = D_4 \times \bar{R}$ 0.94

Range Chart Lower Control Limit Formula

$LCLr = D_3 \times \bar{R} = 0$

PERIOD USED TO CALCULATE CONTROL LIMITS

From: 15 9 03 To: 30 10 03

Pp = **Ppk =**

Cp = 1.96 **Cpk =** 1.50

PERIOD USED TO CALCULATE CAPABILITY

From: To:

SAMPLE SIZE	CONSTANTS		
n	d2	D3	D4
2	1.13	0	3.268
3	1.69	0	2.574
4	2.06	0	2.282
5	2.33	0	2.114

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Figure 4: Enlargement of right bottom corner of Figure 3, showing process average, range average, control limits, Cp and Cpk, and Hartley's constants for estimating standard deviations.

The purpose of the SPC chart is to monitor the process and to highlight changes that have happened well before items out of specification are produced. The constant core question is, 'Is the process in control?' In SPC theory, a process is 'in control' if its measured outputs are predictably within certain limits.

There is an important and often misunderstood distinction between *specification limits* and *control limits*. The former define the range of variability allowed for a product to be usable (which may be defined by customers, legal requirements or internal company requirements). By contrast, the control limits are statistically defined from process data. They are based on the mean and standard deviation of the process measurements: the lower control limit is the (mean – 3 SD) and the upper control limit is the (mean + 3 SD). The use of these control limits is based on two assumptions (Alwan & Roberts, 1995):

1. the particular measure of items produced is distributed normally (this might be the means of subsamples),
2. the data are independent and identically distributed.

In such cases we can assume that 99.7% of all measurements will stay within +/- 3 SD of the mean. If the mean is not on target with control limits which have been fixed on the basis of previous capability studies, a smaller percentage will fall within those limits. If data points are non-conforming points (i.e., outside the control limits) or if a trend away from the target is observed, the process has to be investigated.

Another crucial distinction in SPC is that between random *common-cause* variation and *special-cause* variation. Common-cause variation is predictable and leads to almost all data points being within the control limits. Any special cause can lead to patterns or trends which need to be investigated. To detect these potential deviations in the charts SPC experts in a company specify probability-based rules as an ‘action plan’. For example, the chance of seven consecutive points above or below the mean has a probability of 2*(1/2)^7=1/64, which is quite small to be caused by random effects, and observing such a sequence of points is an alert to look for a special cause having developed (for example, a broken or worn machine part). In this way, SPC charts can be useful to detect deviations from the normal situation and to seek to remove the special causes which create those deviations (Oakland, 2003).

In a complex manufacturing operation such as car manufacture, not all processes are subject to SPC. It is used for legally regulated processes (e.g. to ensure the safety of steering or brake systems) or expensive processes where precision is a known problem; it would not be applied to processes where the outcomes are non-functional and invisible to the end user (e.g. lengths of wiring and tubing). At Classic Motors, SPC data are sent to the plant’s SPC Department, where control limits and other measures are calculated and returned to the production area for future reference and feedback. Amongst these measures are the process capability indices.

4.2 Process Capability Indices (PCIs)

Process capability indices (Anis, 2008; Kotz & Johnson, 1993) measure some key characteristic of a production process. In Figure 1 this was the mass of bolts. Figure 3 concerned the width of tox strips: if too narrow, rain might enter the car; if too wide, the windscreen might not fit in the metal frame. The simplest process capability index is termed ‘Cp’ [‘see p’], which is defined as follows:

$$C_p = \frac{USL - LSL}{6\sigma}$$

where: USL = upper specification limit

LSL = lower specification limit

σ = standard deviation

It takes into account the ratio between the tolerance (range of tolerated values: USL – LSL) and the process variation over a particular period of time. This variation should be small compared to the tolerance so that some drift of the process mean does not lead to problems. It is important that the process distribution is so ‘tight’ that products produced outside control limits are still within specification. A rule of thumb is that the proportion of the distance between the specification limits (USL – LSL) to the distance between the control limits (UCL – LCL = 6 SD) should be at least 4 : 3. This gives the process some space to manoeuvre and the mean to move slightly off target (as in Figure 3).

One drawback of Cp is that it does not take the location of the mean into account, so a process may have very low variability, and yet be uselessly off target (i.e., centred far from the target). A second measure, Cpk, defined in Section 1, does take the process mean into account. A process is called *stable* if it stays within the control limits determined by previous process runs, and *capable* if Cpk is large enough. Cpk is usually required to be at least 1.33 (4/3), but Classic Motors have also used 1.5 and 1.67 in the past. One might conclude that a higher Cpk is always better than a lower one, but a Cpk can be unreasonably high. It might not be cost effective to reduce variation beyond a certain point, or specification limits might be too wide. One might expect that Cp is too simple to be usable, but it is still a useful measure, for example if the process mean is known to be too high or low and there is improvement work going on to change it. (For visualisations of Cp and Cpk, see section 6.1, which also has a weblink to run the visualisation tools that we developed.)

5. PROBLEMS WITH SPC IN PRACTICE AND TRAINING

Having provided general and technical background to SPC we can now answer the first research question on problems with SPC in practice and training.

5.1 Problems in Practice

We heard that managers sometimes expect ‘magic’ from statistical techniques, but analysis by itself can never improve a process. Engineering expertise is required to investigate the process and statistical measures have to be interpreted with caution and an awareness of unfulfilled assumptions. Communication between different communities such as shift leaders, operators and engineers is required to improve production processes and maintain quality standards. We wondered why all operators needed to know about SPC. One of the typical answers we received was that during night shifts, there were generally no engineers or managers around to advise employees faced with breakdowns. Shift leaders are therefore expected not only correctly to detect but also to solve the problems themselves.

Furthermore, if shifts in measures pointing to process deterioration are ignored, an emerging and potentially expensive breakdown may not be noticed in time (for an example see Hoyles et al., 2007). Nor does a high Cpk number necessarily signify a good process or product. We learnt that component suppliers to the factory sometimes manipulate their product specifications to give their products an artificially high Cpk, to try and impress the manufacturer. Dealing with such suppliers may be the job of a first-level manager on the shopfloor with limited educational background. These examples illustrate the need for employees to understand about PCIs beyond the superficial knowledge that PCIs should be at least 1.33.

We have seen much confusion of *specification* and *control* limits, not only in Classic Motors but also in the pharmaceutical and packaging industry (Hoyles et al., 2007). Many employees interpret control limits as specification limits. It is crucial to know whether these are outside the control limits (which can happen by chance even in stable processes) or outside the specification limits (to be avoided by all means).

It is also crucial for employees to distinguish between *common-cause* and *special-cause* variation. Random variation occasionally leads to ‘peaks or troughs’, and if the process is stable one should not change the settings. However, we heard many complaints from engineers and managers that operators and shift leaders often ‘chase ghosts’ or ‘tamper’ with the process by adjusting it when one data point is higher or lower than most other points. This generally leads to deterioration of the production process. One engineer reported that some companies have control panels for operators that are partially fake: critical settings can not be changed through them even though operators believe they can!

In Classic Motors, shift leaders to whom we spoke were used to having SPC charts on their notice boards, but to most operators and shift leaders the PCIs seemed rather alien things that were often ignored. At best these indices were mainly understood as what we call ‘pseudo-mathematics’: as labels for good or bad processes which do or not meet required targets (such as Cpk = 1.33) without meaningful connection to their basis in the manufacturing process. Yet the company wanted the indices to be meaningful as prompts for appropriate action, and invested in training to help employees to do this.

Many employees we met had been trained in SPC and knew the standard mantras, for example that variation should be reduced (but not at any cost). Perhaps more importantly, they seemed to know what SPC meant in practice in terms of collecting data and writing down annotations on the charts (in clouds, as in Figure 5) to record potential causes of outliers or patterns in the data. Yet our impression from the interviews was that they generally had sketchy knowledge of what the statistical concepts meant in terms of the physical production process. We saw some tendency to use PCIs as a target (e.g., 1.33) but not to have a meaning for the number in terms of performance in relation to specification, or being able to recognise the role of PCIs in taking a poorly performing process and improving it. In short, although the SPC charts seemed to serve their communicative role moderately well, the PCIs did not function as boundary objects.

5.2 Problems in the Training Course

The way in which the workplace trainers generally tried to make the central ideas of SPC accessible to employees was by means of analogies and a simulation of the variability of production processes; in this case the simulation took the form of a hypothetical manufacturing problem for the Government Mint of coins that were stamped out with sides too rough and had to be buffed smooth. The ‘buffing machine’ simulation was based on ‘shove ha’penny’, a traditional British board game in which coins are pushed along a board to stop at a specified grid space; the specification for the machine was to achieve a target of 9 ‘buffs’ (i.e. to stop in the 9 grid space) with an allowed range of +/- 2 ‘buffs’. Several rounds of the simulation were used. In the first round, the participants tried to hit the target (9 in the SPC chart in Figure 5) by pushing a coin by hand; this led to huge variability and low Cp and Cpk values. In the second round (represented in the second half of Figure 5), they used a clamped ruler as a launcher with controlled variable strength to apply a more constant force on the coins. This led to a less variable process and better Cp and Cpk values. The simulation gave course participants direct experience in collecting samples of process data, manually calculating statistical measures, and devising mechanical improvements to the process which resulted in improved statistical measures (better fit of data to target value and smaller data spread). The rounds were time-consuming, each took more than an hour, and calculations were sometimes left to one (already-capable) person in the group.

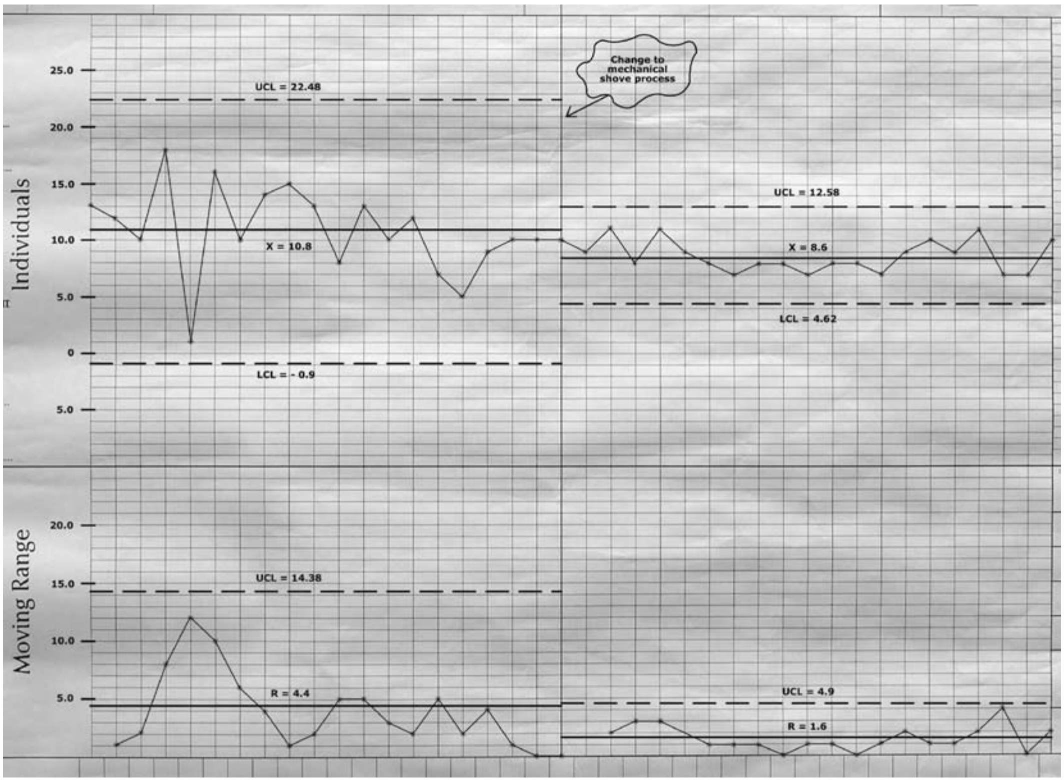
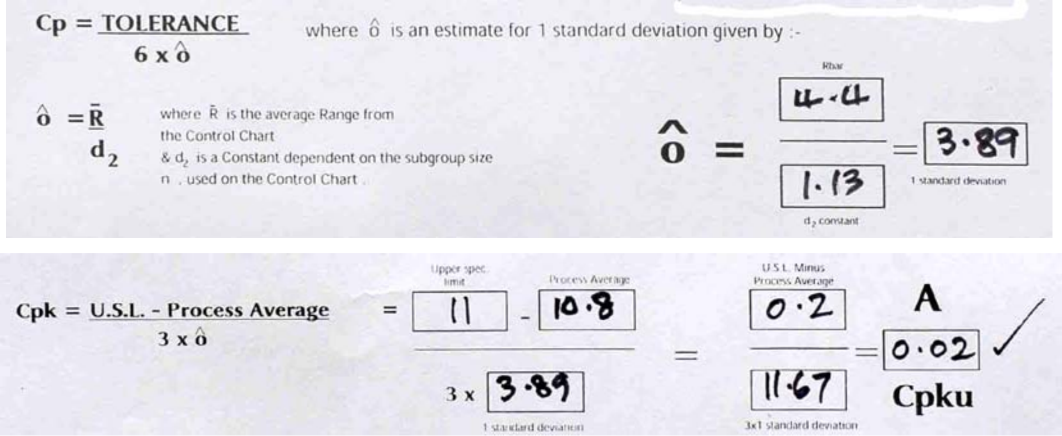


Figure 5: Reconstruction of an SPC chart filled in for two rounds of the buffing machine. The second (right) half of the chart stems from the second round in which a mechanical 'launcher' using a clamped ruler was devised by the participants. The cloud contains a comment: "change to mechanical shove process".



$Cp = \frac{\text{TOLERANCE}}{6 \times \hat{o}}$ where ô is an estimate for 1 standard deviation given by :-

$\hat{o} = \frac{\bar{R}}{d_2}$ where $\bar{R}$ is the average Range from the Control Chart & d_2 is a Constant dependent on the subgroup size n . used on the Control Chart .

Rbar

$\hat{o} = \frac{\boxed{4.4}}{\boxed{1.13}} = \boxed{3.89}$

d_2 constant

1 standard deviation

Upper spec. limit

Process Average

U.S.L. Minus Process Average

$Cpk = \frac{\text{U.S.L. - Process Average}}{3 \times \hat{o}} = \frac{\boxed{11} - \boxed{10.8}}{3 \times \boxed{3.89}} = \frac{\boxed{0.2}}{\boxed{11.67}} = \boxed{0.02}$ ✓

1 standard deviation

3x1 standard deviation

A

Cpku

Figure 6: Two parts of the calculation sheet filled in by trainees during the first round (data points 1 to 20). The ô is supposed to be a Greek sigma (which the trainers said they could not access in their word processor).

Based on our observations of the training, analysis of the interviews and the results of the questionnaire distributed to and received back from participants, we summarise our evaluation of the course as follows:

1. Cp and Cpk turned out to be the most difficult concepts addressed in the SPC training and participants found them important: they need to know about them because these measures are part of work practice in many areas of the factory.
2. Calculating these capability indices involved a lot of arithmetic and even algebraic symbols that were unfamiliar to most participants. For example, some did not know that they had to divide two numbers in boxes if there was a horizontal line between them. As Figure 6 shows, formal symbolism was used (even in unconventional ways – see the ô instead of a sigma) and the meaning of Hartley's constant d2 was not explained. Other computational problems were: subtracting before multiplying, not knowing what to do if one box stood over the other (division), subtracting 0, filling in a formula and rounding. We summarised these as 'problems with algebra' and observed that the worksheets with algebraic representations did not seem to enhance their understanding. Peter knew that employees found the algebra hard, but saw no other way of representing the basic statistical ideas involved. We speculated also that he assumed that the mathematical symbols would nevertheless reassure employees that SPC was not a management whim but had an objective 'badge' of authority.
3. The focus on manual calculations required a lot of attention which, in our view, was not directed to the big ideas underlying SPC. One of these is the idea of distribution with centre and variation. Another is that there is a probability that some items (0.27%) produced will fall outside the +/- 3 SD control limits, under the assumption of normally distributed outputs.
4. Peter used many rules of thumb, some of which were not correct from a statistical perspective. For example, he used estimates such as: "if Cpk = 0.8, then 80% of the items produced will be in spec and 20% will be out of spec." Another 'rule' he mentioned was that "with better gauge resolution [more precise measurement], your Cpk will go up". As we describe later, working with the computer tools proved a way for him to test these rules of thumb for himself.

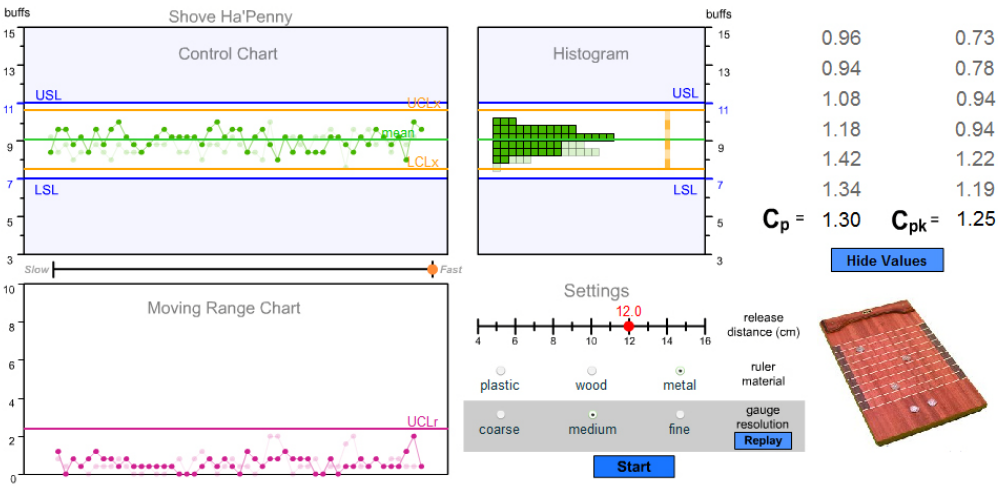
In short, our main observation of the SPC course was that the Cp and Cpk values were generally failing in their intended role as boundary objects. The employees had a strong sense (based on practical experience) of what variation was and why it needed to be measured and controlled, but the means of translating this information into precise statistical form was presented as a piece of school-like algebra, and worse, was performed manually. There was a common bias towards manual calculation among trainers and engineers as being the best way to learn 'how calculations work', and (we inferred) an assumption that technology is only helpful for automating calculations; in contrast, our argument is that computer software can be a means to reveal and explore how calculations work. Unsurprisingly, almost no shopfloor employee we observed or to whom we spoke was comfortable with this means of presentation. This is why we focused our design efforts on the PCIs: by re-presenting them suitably we expected them to become boundary objects. What we needed was a representation of the relevant relationships (the statistical model or structure) between mean, variation, target and limits, which 'bypassed' the algebra and would be easier for engagement by employees. We managed to negotiate collaboration with two SPC trainers, and set out to design technology-enhanced boundary objects (TEBOs) to meet these requirements.

6. CO-DESIGN OF TECHNOLOGY-ENHANCED BOUNDARY OBJECTS

In this section we address the second research question on characteristics of the design process that seem crucial for the tools to become boundary objects.

6.1 Alternative Representations of the Process Capability Indices[1]

We first designed a simulation of the shove ha'penny game (Figure 7) to give trainees a context for learning about the PCIs and to speed up the time-consuming rounds of doing the simulation by hand. The screen representation was modelled very closely on the paper SPC charts used in the company. Like the physical game, the point of this simulation was to give participants a sense of what it means to optimise a process by finding the best combination of settings. An interesting phenomenon was that employees were challenged by the way the tool could produce quite variable values for Cp and Cpk, based on repeated random samples with the same underlying mean and deviation. This is equally true of the physical process, however the variability in that case seems more easily explainable by variability in the physical process.



C_p	C_{pk}
0.96	0.73
0.94	0.78
1.08	0.94
1.18	0.94
1.42	1.22
1.34	1.19
1.30	1.25

release distance (cm): 12.0

ruler material: ○ plastic ○ wood ● metal

gauge resolution: ○ coarse ● medium ○ fine

Figure 7: Shove ha'penny simulation. At the bottom right corner users can change the settings to optimise the process. The upper left chart shows the individual run chart with mean, control limits and specification limits. The upper right chart shows the sideways distribution of individual measurements. The bottom left chart shows the part-to-part variation (absolute differences between consecutive measurements) in a moving range chart.

The main challenge we set ourselves for dealing with Cp and Cpk was to design alternative representations of the process capability indices that would be more

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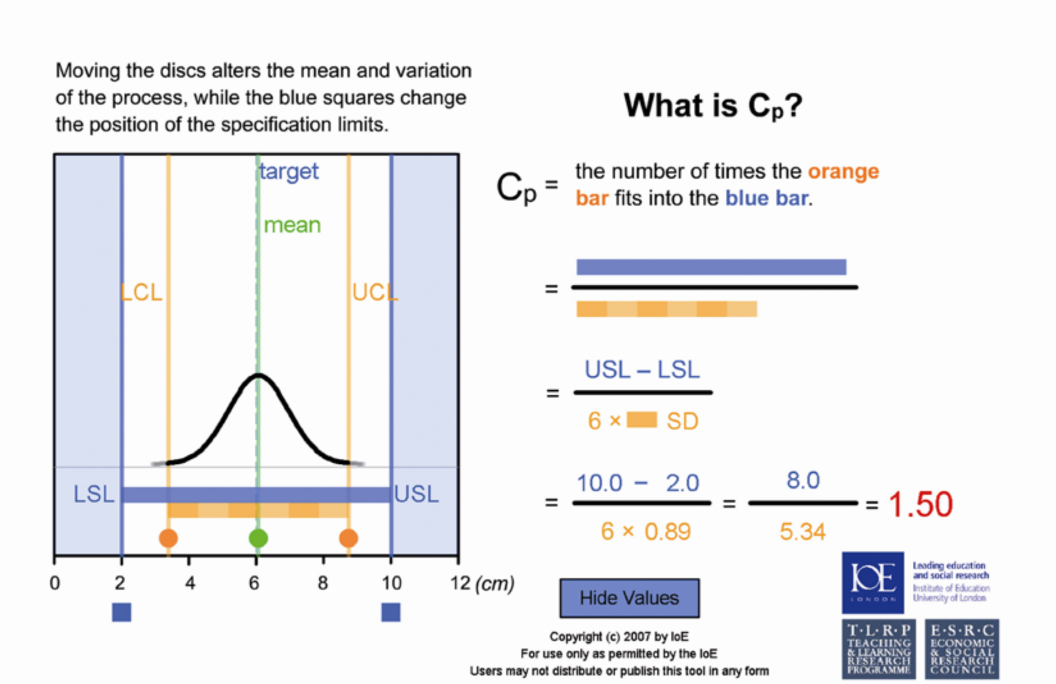
[1] The tools described here can be freely accessed via the website: www.lkl.ac.uk/research/technomaths/tools/spctools . A brief registration is requested to monitor the use of the tools.

engaging than the present formal symbolism used in the manual calculation and training notes (in line with design principle 1). By further developing a computer tool on a constructionist basis (design principle 2) we also intended to give future course participants an opportunity to interact with the ideas, make discoveries about the relevant statistical relationships underlying the PCIs, and map their insights back to their practices. Workplace trainers were involved from an early stage (design principle 3).

In trying to make the mathematical relationships of PCIs easier to engage with and communicate, one key design decision was to represent the two most relevant numbers, engineering tolerance (USL – LSL) and 6 SD, by two bars (Figure 8). The Cp value then becomes ‘the number of times the orange 6 SD bar fits into the blue tolerances bar’. For the Cpk value (Figure 9) this is more complicated: how many times does the orange 3 SD bar fit into the smallest of (USL – mean) and (mean – LSL)? In this way we avoided the conventional algebraic and statistical symbolism. We also aimed to defer attention from numbers per se towards the meaning of the numbers as ratios relating the process distribution to the specification limits. This effect was strengthened in a later version of the tools, by adding the option of hiding the formula and numbers so trainees could check their estimates. The idea of “fitting the process within the spec (tolerance) limits” came from the trainers, which they used extensively through the metaphor of a car park: the process is the car which has to fit in the parking space of the spec limits.


Moving the discs alters the mean and variation of the process, while the blue squares change the position of the specification limits.

What is C_p?

C_p = the number of times the orange bar fits into the blue bar.

$$= \frac{\text{USL} - \text{LSL}}{6 \times \blacksquare\ \text{SD}} = \frac{10.0 - 2.0}{6 \times 0.89} = \frac{8.0}{5.34} = 1.50$$

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Figure 8: The Cp tool. In this case, Cp = 1.5 because the bottom orange bar fits 1.5 times in the top blue one. Here the mean concurs with the target value. The grey ‘tails’ of the distribution curve indicate that there is still a small chance that measurements in a stable process will fall outside the control limits.

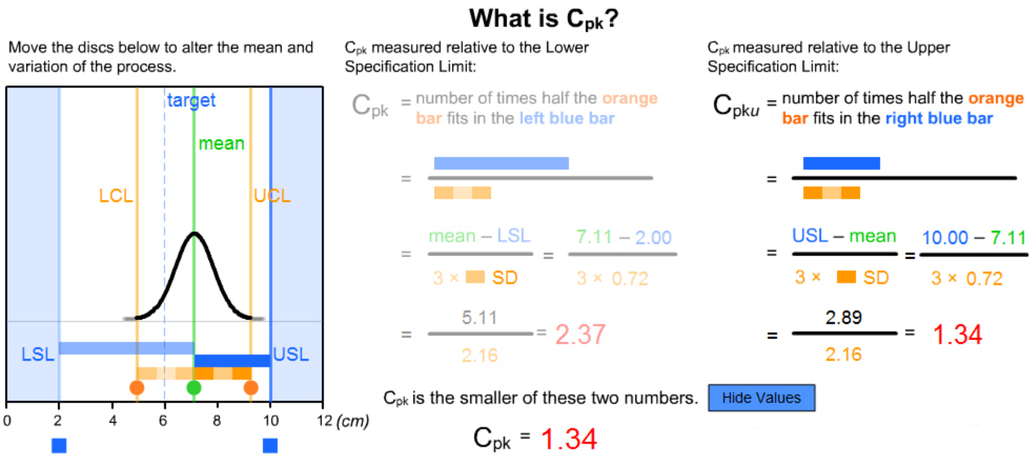


Figure 9: The Cpk tool with values shown; Cpkl is greyed out as it is the larger value. Cpku, the proportion between the dark blue bar (USL – mean) and the dark orange bar (3 SD), equals 1.34. Although this process is slightly off target (mean is 7 instead of 6 cm), there is only a small and (for the car factory) acceptable risk that items of 10 cm or more will be produced.

On the basis of the second, constructionist design principle we aimed for ways in which employees could use more familiar language than the algebraic language used in the course. We found ample evidence (and no counter-evidence) that trainers and trainees used the ratio of bar lengths instead of formulae to estimate PCIs.

6.2 Aligning Statistical and Workplace Norms

For the software tools to be boundary objects, they had to live in different communities and satisfy the informational needs of each. We give a few examples to provide a sense of the required alignment of norms from different communities.

6.2.1 A crucial workplace message

We start with an example of making sure the tools satisfied the trainers' requirements and finding out as researchers what are crucial norms in their work. It concerns the first version of the shove ha'penny tool (Figure 7), which is a reconfiguration of the SPC charts used during the training course (Figure 5) as well as a context for the PCIs (which are calculated in the right-bottom corner of SPC charts, see Figures 3 and 4). In an early version of this tool we had nominated 'operator' as one of the three variables. Possible settings were three different people and our idea was that participants should find the best operator. The trainers, however, noted that one of the core messages during their training is that all work processes should be operator independent. To explain the importance of this, Peter gave an example:

> You tend to find people with particular talent, and they want to know why you can't use John because he is superb. What happens if John is off sick, or on holiday. You can't put a note in the glove box that states, "There is no windscreen today, because the windscreen fitter is on holiday. I am sure you will understand."

Hence we had to determine a choice of variable other than operators. After brainstorming and negotiation with the trainers we settled on ruler material with three different settings – plastic, wood and metal – which we designed to lead to different variation in the data (Figure 7).

6.2.2 Statistical versus workplace meanings of Cpk

This particular example shows how the co-design of the tools revealed the different views on Cpk from different communities. The statistical definition of Cpk is the minimum of the lower and upper Cpk (Cpkl and Cpku) so we made two columns in the Cpk tool – one for Cpkl and one for Cpku (Figure 9). We expected users to estimate both values and take the minimum – according to the definition. We were so conditioned by the textbook definition that we had not anticipated Peter's, and his colleague Sean's, more context-based view:

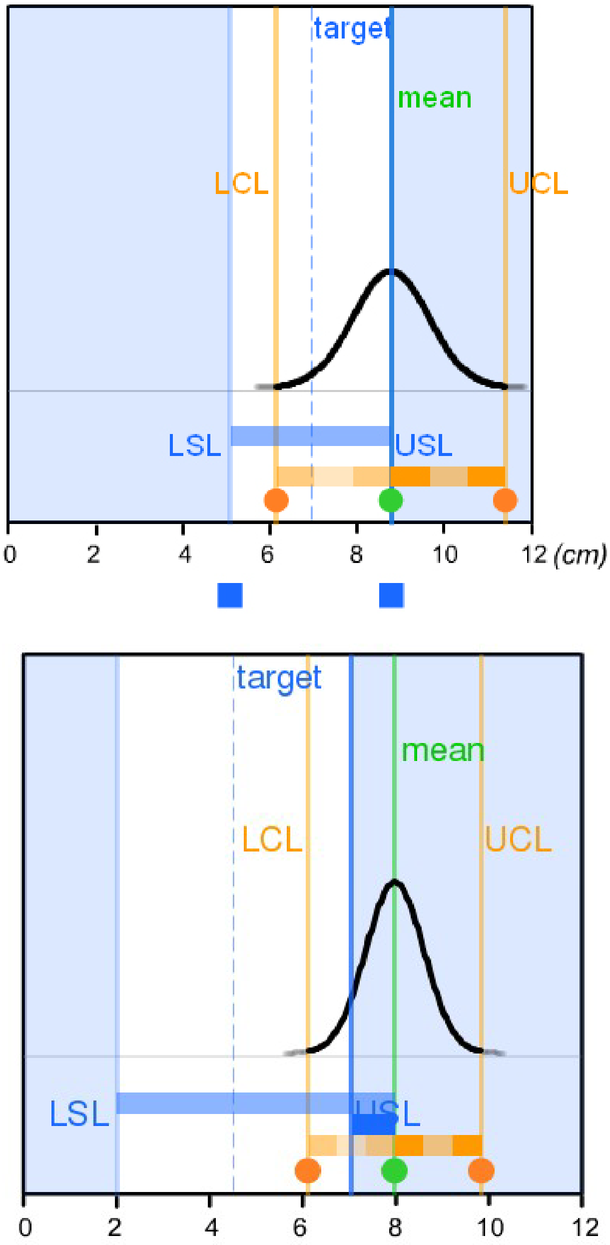
> S: All we ever talk about is the closest specification [lower or upper].
>
> P: The side that is most at risk.
>
> S: We never actually say "the minimum of".
>
> P: No.

Because they were only interested in the side of the process that was 'at risk' of violating a specification limit, Sean suggested greying out the side of the calculation (Cpkl or Cpku) that was irrelevant, which led to some discussion amongst the team. Some of us, thinking of our educational mantras, argued we should not take away the opportunity for participants to discover that only the at-risk side needs investigation. Why not let users discover for themselves that they only had to look at one aspect? Ultimately, however, we decided to follow Sean's suggestion because the Cpk concept was already difficult enough for most employees, and their attention was better directed to other messages about Cpk the trainers hoped to get across, for example "the higher Cpk the better" but without short-cut manipulations such as widening the specification limits.

More generally, the discrepancy between the statistical definition of Cpk and the workplace meaning attributed to it by the trainers hints at a crucial point. When defining a precise measure such as Cpk, it has to be formalised into a statistically sound definition and then shaped in a form that is different from how it is interpreted in practice. When learning the statistical definition, learners have to undergo a reverse process: what is the core idea that was formalised here? Or: what workplace meanings should be attributed to this statistical meaning? Discussion of the software tool helped us coordinate these two 'world views', and eventually the trainers received a tool useful for their purposes.

6.2.3 Becoming aware of fragmented knowledge

The previous examples illustrate how we enhanced our view on SPC, which was originally shaped by the literature and our ethnographic case studies, and became more aware of workplace norms and meanings. In other words, one feature of the TEBOs was they helped make explicit our and the trainers' implicit assumptions. In this next example Peter and Sean discovered facts that were different from their expectations. For instance when they explored the Cpk tool they discovered that some of their rules of thumb were formally incorrect. We mentioned earlier that Peter used rules of thumb such as: "if Cpk = 0.8 then 80% of what we produce is in spec and 20% out of spec” (hence if Cpk = 0 then none is in spec). This reasoning puzzled us for a long time: it appears true only for processes uniformly distributed (rather than normally) that are centred on target, and it made sense only for 0 < Cpk < 1.



(a)

(b)

Figure 10: ‘Confusing’ cases of Cpk. a) Cpk = 0, and b) Cpk = –0.5 . In a) the mean coincides with the Upper Specification Limit (USL)

It was when testing the learning opportunities that Peter and Sean made their discoveries:

Res.:	How about making a Cpk of negative 0.5?
P:	It needs to be *all* outside specification and a little bit more. Minus 0.5 means that what you are building is outside spec.
Res.:	What does that mean?
P:	The minus. Nothing that you build is within specification. (…)

> P: If you just press “show” it should tell us. (…). Hang on a minute. Hang on! (…) We are getting confused on this one.

Note that Peter appeared to be using his rule of thumb in the second line, but realised, in the last line, that his reasoning based on this did not lead to the right results. He and Sean next tried to make a curve with Cpk = 0. According to the rule of thumb everything should be out of spec, but they discovered a problem with this assumption when using the tool:

> P: Come on, try that [shifting the tool handles such that Cpk = 0]. So half of it is within specification and half outside. It is me that is confused.

In line with design principle 2, he thus discovered another fact, “Cpk = 0 means half in spec” (see Figure 10a), which contradicted his rule of thumb. After the meeting he told us, “I have never thought of 0 until that came up”.

At this point, we thought he had concluded that his rule of thumb was ineffectual. We were inclined to claim the TEBO had done its work as a mediating tool for communicating about Cpk and engaging with the statistical ideas behind it, but – as we describe later – we were too presumptuous. Peter did not arrive at the conclusion in the sense that he gave up using the statistically incorrect rule. Five months later during the second course, when explaining the shove ha’penny simulation he used the same rule of thumb that underlay his Cpk = 0 mistake. During the same course he repeatedly mentioned how confusing he found the case of Cpk = 0, referring back to the discovery he made at the first co-design meeting.

We were intrigued that Peter could use his rule of thumb whilst at the same time acknowledging his discovery of Cpk = 0 at the same time, and so we sent him an email asking for further information on this. He responded:

> Whoops - a slip of the tongue, in order for everything to be out of spec the Cpk needs to be at least Cpk = -1. My gu-estimates should refer to Cp values and in the examples quoted [Cp=0.17, 0.02 & 0.4], and very roughly speaking, (at best) 83%, 98% & 60% will be out of spec. I know that strictly speaking this isn’t so - it doesn’t take the tails of the distribution into consideration. It also only works for values less than 1, in that even if the process was perfectly centred the spread would be greater than the tolerance, values equal to or greater than 1 merely indicate the potential for the "spread" to fit within tolerance. Thank heavens for judicious editing!

This example illustrates that the coordination of bits of knowledge is non-trivial and takes time. Even though Peter seemed to have discovered the fact that Cpk = 0 means half the process is out of spec, this was an isolated fact and seemed to co-exist next to “Cpk = 0.02 means almost everything of what we build is out of spec”, which relied on his rule of thumb. We speculate that, within the context of training, Peter tries to give participants a sense of how bad a process can be with certain Cpk values, and by being pessimistic about the percentage of items produced out of spec stays on the safe side. More generally, we observe that Peter’s thinking drew on rich experience of being on the assembly line and the ‘rules’, in their limited and fragmented way, might yet be practical advice for the way an operator thinks on the line.

7. THE TOOLS AS TECHNOLOGY-ENHANCED BOUNDARY OBJECTS

The third research question, whether the computer tools would come to function as boundary objects, is addressed in this section. In terms of Figure 2 we continue to discuss the tools in use with trainees (stage 2), between trainers and trainees (stage 3), between a trainee and a supplier (stage 4), and lastly between trainers, managers and engineers (stage 5).

7.1 The Computer Tools during the Training Courses (Stage 2)

We give two examples: one of the trainees quickly becoming adept in estimating process capability indices, and a set of feedback comments that show trainees' appreciation of the tools.

7.1.2 Cpk = 0

Peter asked us to use the question about Cpk = 0 in the learning activities as he had found it "a killer question". The participants in the second course were mainly apprentices, and had never heard about Cp and Cpk but they quickly became accurate estimators of those values and said they understood what these values represented, even in the case of Cpk = 0. When comparing our observations of participants manually calculating Cp and Cpk with observations of the three courses, we concluded it seemed crucial that users of the Cp and Cpk tools merely needed to estimate the number of times the orange bar fitted into the blue bar, rather than performing a complex calculation involving an algebraic formula. It appeared the tool did help to make the ideas behind the process capability indices clearer because the 'fit' metaphor can be used to make appropriate estimates.

7.1.2 Highlights of evaluation

The learning opportunities were received very positively by trainers and participants. To illustrate a variety of feedback comments we select a few of the clearest (we have had no negative feedback). After the first course, participants were often pleased to have learned more about the Cp and Cpk measures. During a telephone interview one said:

> Now when I go to meetings I know what they are talking about, whereas before I would think "what the hell's a Cpk", whereas now I know and understand what they're talking about.

After the second course, one apprentice summarised his view about the learning opportunities as follows:

> 1. It is a lot more interesting to use the tools rather than just doing the algebra.
> 2. It is faster to use the tools because it calculates everything automatically.
> 3. The visual aid also helps to see what is happening, instead of numbers alone.

Another participant: "The interactive nature of the software is, I feel, advantageous when understanding the principles." After the third course, amongst the feedback were the following comments:

> Greatly enhances visual understanding of Cp and Cpk values. Enables you to play around with the values without having to do constant calculations.
>
> Using the tools on laptop helped my understanding and made me more confident.

From the feedback and our observations during the courses, as well as the trainers' comments we concluded the computer tools succeeded in representing PCIs in a way that enabled employees to engage with these numbers.

7.2 Training without Our Presence (Stage 3)

We were not directly involved in the remaining phases of the tools' trajectory. We quote from interviews to show the computer tools satisfied many employees' needs and can reasonably be called boundary objects.

One very experienced quality engineer (QE, director of 250 engineers in the UK) told us that our intervention with the tools had had an impact on their training courses.

> QE: The tool itself can be replicated by Excel or by Minitab or any other statistical package in terms of representing the data, but what it does do is, it made us question how we deliver the training in terms of process capability.
>
> Res.: Did you? You questioned it?
>
> QE: Yes, because if someone is offering a different perspective of how it was being done, is there a better way? Then you take, should take note of that, and analyse on how it's changed, because it's changed certain behaviours within training sessions.

The engineer told us that he had changed his pedagogy away from performing calculations and towards the 'reasoning behind it', advice also recommended by Chance et al. (2007).

Peter had also rethought his pedagogy, in terms of the analogies he used. At the dissemination meeting, at the end of the project, he stated:

> Cp and Cpk, prior as to using those, we tried to explain the difficult concept with a car in a garage. We compared the spread of the process with the size of the car and the tolerance with the [space between] the white lines. Cp is relatively easy. My car has the same potential to fit in the car parking space as the managing director's. In reality, he parks outside the office, and I park half a mile away. So the Cpk has a concept [we assume he means: there is a reason for Cpk]. It is no longer where it needs to be. But again it was extremely difficult to put across.

He explained the dynamic tools made it easier to explain Cpk:

> One of the hardest things we have to get across is what the Cpk means – once you're familiar it becomes trivial, but to translate that to someone who doesn't know is really difficult, the tool enables you to show in a dynamic way – if I move this then this moves. It's like creating a cartoon from a load of slides. When the operators chart data they are taking little snapshots in time and your tool brings it all together like a cartoon, animating it.
>
> The tool makes it very, very visual. And the guys themselves can play with the distribution, and they can move it as they will, and they can see, hopefully, that the Cp value does not change.

We asked Peter whether he foresaw himself using the tools as part of his courses, to which he answered:

> Yes, I have already used it in some follow-up courses, and I have given the link [to the software tools] freely to people within the [factory] site. I have sent it to managers, so the managers can use the tools as well. And I am also trying to promote it on the supplier base because after all the aim is not that just we build parts to Cpk values but also our suppliers give us parts that are fit for purpose.

Our intention in designing the tools was to enhance existing SPC training, and the interviews show this happened. There are examples, however, of unintended use of the TEBOs. Peter's last remark hints at the tools being used with suppliers and we discuss this in the following two sections.

7.3 Communication between Trainee and Supplier (Stage 4)

One of the measures of a successful boundary object is its impact in practice so we tried to gauge if, and how, some of the course participants used the tools in practice. In a post-course email interview a participant, Dan, wrote to us that he had bookmarked our website immediately after the course and had used the computer tools many times since then. When asked what exactly made the tools so invaluable, he responded, "The dynamic interaction made the Cpk tangible as opposed to the algebraic formulae being a bunch of numbers until they where calculated." To discover how Dan used the tools, we arranged a telephone interview, in which he explained how he had solved a concrete problem whilst using the Cp tool.

The problem was that in some estate cars very little water was emerging from the rear washer jet. After investigation they found that faulty rubber tubes running from the water reservoir in the engine compartment via the roof to the washer jet had a kink, which prevented water going through the tube. The faulty tubes had a large overhang (the length of the tube hanging off the back of the car), and pushing this into the roof body, during assembly, caused the kinking. In line with the process improvement mantras, Dan started measuring the tubing received from the supplier and noted a range from -4 mm up to 50 mm overhang, whereas 10 mm is the target (-4 means that the tube is 4 mm too short). He knew that operators just pushed the overhang in the tube back into the roof of the car. The assumption was that with large overhang if "you push it back on itself, it'll make a big arc", but nobody had realised, until Dan actually started measuring, that with a range of smaller overhangs "it just kinks" and "then restricts the water coming from the washer jet."

Once he had collected his data, he tried to map them mentally to the curve in the Cp tool he had learnt to use in the SPC course. He told us (with poetic resonance):

> I look at your tool, put my numbers against yours, and drag them sideways, and just watch the waves spread into a little ripple, and then, you know, it's miles out of spec.

We assume he interpreted the '5 cm' shown in the software tool as representing a 50 mm overhang. Apparently he used the tool as a model of how processes should appear and, when looking at our tools, he also realised that "we did not have a tolerance".

> Interv.: Has using the Cpk tool made you realise the spread of the process?
>
> Dan: Oh god yes, not half. They [supplier] just said 'our tube is 2.8 m long, what's that got to with 10 mil [mm] hanging off the back'. That was of no consequence to them.

The tube supplier ensured that it supplied 2.8-meter tube lengths, plus *some* overhang, but had no understanding of what the *acceptable range* of overhang was for the tube to function correctly. The car manufacturer had merely asked for a 10 mm overhang and had not given the supplier any specification limits resulting in too wide a range of tube lengths, a particular subrange of which led to kinked tubes.

What followed was a data-informed discussion between the car manufacturer and the supplier of the tubes. The big advantage of collecting data was this discussion was based on facts, not opinions. In Dan's words:

> [Before] I would simply have said, "I think they are too long" (…) now it's a fact. The fact that all these tubes are these lengths and they're causing a problem is not because I think they are a bit longer than they should be, it's the fact of the measurement, and a rubber tube of a certain diameter bent at a certain angle will kink at, I dunno, 80 degrees. And it's gonna kink every time, it's a mathematical fact. So we knew it had to be under a certain length not to kink, we had all the information.

This example shows Dan had incorporated our Cp tool into his kit for problem solving, but he used it in a non-standard way. He recontextualised the tool in a new situation, in which Cp and Cpk should not have been helpful as there were no specification limits. We conjecture that he realised the problem of specification limits because he tried to map his data onto the Cp tool. Thus, although the tool was designed for understanding Cp and Cpk, here it mediated his thinking for a different purpose. This means that, in this case, design principle 2 worked in practice, in particular in mapping meanings of symbolic artefacts back onto their own workplace setting.

Note the computer tool did not literally serve as a boundary object between Dan and the supplier, because the supplier did not see the tool, but it had helped Dan focus on crucial mathematical relationships, in this case to include specification limits, which helped him communicate quantitative information to the supplier.

7.4 The Tools' Further Life (Stage 5)

Although the tools at first seemed rather simple pictorial reconfigurations of formally defined and taught statistical measures, they were very well received. We give a few examples, from the time after our direct involvement, which support our claim that the tools were TEBOs.

7.4.1 "Inputting our own data"

One of the requests repeatedly heard was for users to be able to "input their own data". We think this was a request to be able to set the scales of the tools to the actual numbers used in their own process data:

> would it be possible to enable the web tools to accept different numbers - it would be quite a powerful tool if we could input our own tolerances and spread numbers? Then it could give an instant representation of real processes - we could then demonstrate to shopfloor teams exactly how their processes are performing in relation to customer expectations (specifications). [Peter, SPC trainer, Classic Motors]

There was no money left in the budget for the project to do this but Classic Motors proposed re-programming the tools to allow further development.

7.4.2 Managers and engineers

Although the tools were developed for enhancing training courses, they also emerged as useful for communication between managers and engineers to explore hypothetical situations. The quality engineer (QE) cited earlier in Section 7.2 told us:

> In terms of the senior management, one would hope that they have an in-depth understanding of variability and design methods. It is not always the case, and they might be reticent to admit that. And therefore using the tool, I would ask the same what-if questions or at least describe the scenario and in an abstract form say "the consequence of this action is", rather than putting up a page and a half of standard deviation calculations and mean calculations. You say that describes the population, if we do this the consequence will be X and the estimated cost effect will be Y, in the abstract form. And that led to a better dialogue than sending out a [numerical] analysis,

According to the engineer our tools afforded exploration of 'what-if scenarios' (cf. Chance et al., 2007). Software tools such as Excel and Minitab can do so by changing numerical input data but they lack the capability of permitting direct manipulation of a distribution shape.

7.4.3 The tools are discovered by another company

We were approached by a small UK company, a specialist automotive supplier of insulation components, that had found a link to our website whilst doing an internet search on Cp and Cpk. The company had no SPC training of shopfloor employees and was considering creating such a training course. It was striking to hear the same concerns, as at Classic Motors, about a lack of understanding of PCI, from the perspective of a component supplier, which has to quote Cp and Cpk to car companies, and receives similar quotes from its own suppliers. A particular issue for this 200-employee company was that the overheads of developing training materials were high, and there was uncertainty as to the cost effectiveness of implementing an SPC training programme.

7.4.4 Global dissemination of the tool

Phil, the SPC trainer from Sporting Motors demonstrated the software tools at several international conferences of SPC specialists. He emailed us that each time he was "mobbed" by people who wanted to have the link to the website. Visitors to the website have originated from the USA, Canada, Sweden, Germany, Turkey, and other countries. In brief feedback, visitor comments confirm the impression from Classic Motors and Sporting Motors that PCIs were little understood concepts, and that the representation of the tools offered a novel way of thinking about PCI relevant to shopfloor employees, engineers and managers.

In summary, we conclude these cases show that TEBOs have proven successful. In fact, our collaboration with these car companies was the most productive in our research. In the discussion that follows, we will consider the conditions that might have facilitated the success of the co-design of the computer tools.

8. DISCUSSION

8.1 Problems with SPC

The car company in which we carried out the research reported in this paper had implemented many process improvement techniques. The effect was that even employees with little background in mathematics, statistics or science needed to engage with such techniques, including statistical process control (SPC). This raised questions about problems that employees experienced with communication about statistical measures, and how they can be addressed.

To answer the first research question, relating to the exact problems with SPC, we focused on SPC charts and particularly the PCIs – wondering if they functioned as boundary objects. Employees were used to having SPC charts in their areas and interpreted them reasonably well, but found PCIs difficult to interpret and communicate.

8.2 Characteristics of the Design Process

Because trainers and trainees found PCIs important we co-designed, with SPC trainers, three computer tools which were meant to enhance existing SPC training, particularly on process capability. The characteristics of the design process that stimulated the tools to become boundary objects can be summarised follows:

1. re-presenting algebraic formalism in a way that does not draw attention to calculations (6.1);
2. aligning statistical with workplace norms and meanings (6.2).

We discuss these points below.

8.2.1 Alternative representations of PCIs

Rather than looking for ways to ‘teach’ one-number measures, we developed ways to build on what employees already knew, i.e. they know a great deal about their production process but little about formal mathematics or statistics. In accordance with our first design principle, we reconfigured important artefacts into three computer tools such that relevant mathematical structures became easier to engage with for employees due to the alternative representations. A key step in the design was to represent the ratio of the distance between the specification limits to 6 SD as two bars. The question of how many times the orange (6 or 3 SD) bar fitted into the blue (USL – LCL) replaced the calculation required in the formulae for Cp and Cpk. This implies that the boundary objects in the training stage (and beyond) were the computer tools, and not the original SPC charts and PCIs anymore. One advantage of this way of technologically enhancing original boundary objects is that it gives designers and trainers a way to draw attention to what they think is important (the ratio of tolerance to process variation) and away from technical calculations (cf. Chance et al., 2007). Thinking about the algebraically formulated relationships seems to break employees’ connections with their production processes, whereas the visual approach taken with the tools helped employees to interpret the distribution curve as their process, which had to be within narrow margins and on target. For a summative comparison of the original and our alternative representations see Table 1.

Table 1: Overview of differences between original and alternative representations

Original representation	*Alternative representation*
Intended boundary objects: - SPC chart (Figures 3 and 5) - Cp - Cpk	Technology-enhanced boundary objects: - Shove ha'penny tool (Figure 7) - Cp tool (Figure 8) - Cpk tool (Figure 9)
Represented as formulae: Cpk (in Section 1) and Cp (in Section 4.2)	Represented as visual image, with direct manipulation of curve and limits
Focus on calculation	Focus on relationships between variables and what-if scenarios
Evaluated as important but hard to understand	Evaluated as easy to use and communicate

8.2.2 Boundary crossing between statistical and workplace perspectives

In answer to the second research question, we can characterise the co-design process as a form of boundary crossing (Engeström et al., 1995; Tuomi-Gröhn & Engeström, 2003), with interaction between different communities enabling learning of each others' values and knowledge. This boundary-crossing approach helped us investigate trainers' views and to revise the tools so they would be more useful for the company and to our research. In this way the tools confronted both us and the trainers with implicit assumptions which sometimes proved incorrect. Thus co-design is crucial in working towards boundary objects because implicit assumptions and goals have to be coordinated for the tools to be useful for different communities. Additionally, co-design increases the trainers' feelings of ownership.

8.3 The Tools as TEBOs

To judge whether the computer tools were in fact successful technology-enhanced boundary objects (TEBOs), the third research question, we analysed their impact on practice at different stages of their trajectory. In the second stage, when the tools were used as part of three training courses, participants were quick to estimate PCIs correctly and highly valued the visual and interactive features of the tools. The algebraic and statistical symbolism that proved an obstacle in previous courses had been 'bypassed'. Subsequently, after we stopped observing their use directly, the tools have been used in ways we could not have foreseen. To our surprise, several trainers had rethought their pedagogical approach and acknowledged the limitations of the analogies they used in their training courses. The tools proved viable in facilitating communication between managers and engineers and suppliers, and managers from companies outside the car industry expressed interest in the tools. In short, the continued use of the tools beyond the research project's direct involvement confirms their success as TEBOs.

Generalising our experiences, we think carefully co-designed tools that represent statistical relationships in non-algebraic ways can help employees engage with statistical ideas that are relevant to their practice but hard to appreciate in the algebraic language normally used in training courses. Such tools can help them connect familiar workplace artefacts to their statistical structures and promote communication between employees.

8.4 Conditions for Success?

We have wondered why our collaboration in the car companies was so much more successful than that with other companies (see Hoyles et al., in press). Before we speculate on the conditions which might have facilitated this success, we summarise our approach. This was to

1. identify problems in practice and training;
2. collaborate with workplace trainers to design TEBOs;
3. use TEBOs in training courses;
4. stay in touch with the trainers to keep track of the TEBOs' lives.

We are convinced that our initial contact in Classic Motors being with a high-level manager with faith in our expertise was a crucial first step. He provided us with access to the right people which, in our experience, is one of the hardest parts of workplace research. Secondly, the car company wanted to be "best in class" and one of its most efficient plants was willing to invest in working with us, the educational researchers. Companies that put less emphasis on continuous process improvement often assumed their return on investing in our research might not be worth their time (= money). We think our approach in reconfiguring familiar artefacts and aligning TEBOs with workplace requirements has the potential to improve workplace communication about statistical measures such as PCIs. Thirdly, in the two car companies we were able to work with trainers who were in stable work environments and not reassigned to other jobs or subject to workplace reorganisations that hindered our collaboration. In other companies with whom we worked we often faced such obstacles.

A final point about statistical software and representation design: visual tools in the form of statistical software (Excel, Minitab) were available in Classic Motors and Sporting Motors to make representations of capability data, but this software does not have the kind of 'direct manipulation of distributions' visualisation which we developed, and which proved so successful. Using direct manipulation rather than changing the distribution through the modification of numerical input data is actually quite an odd idea from the viewpoint of formal statistics – the logic is that the distribution arises out of a sample data set, so to modify the distribution independently of any change in data does not 'make sense'. The lack of concern for thinking about novel representations in professional life is striking compared with the huge amount of effort in statistics education to produce more meaningful software, and better visualisations or representations for learners (e.g., Finzer et al., 2007; Konold & Miller, 2005; Konold & Kazak, 2008). We should bear in mind however that industrial culture is not open with respect to knowledge – knowledge is a commercial commodity for which expert employees and outside consultants have interests in *not* sharing openly. However, our research suggests that making knowledge and suitable representation a focus of employment development can have benefits for improving the practice of communication about process improvement and hence give a boost to commercial efficiency and profitability.

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