F Pavese, A Bošnjaković, S Eichstädt, A B Forbes, J Alves e Sousa (eds.):
Advanced Mathematical and Computational Tools in Metrology and Testing XIII
Series on Advances in Mathematics for Applied Sciences, Vol. 94

https://doi.org/10.1142/9789819800674_0019

# A SQC proposal for monitoring the shipyard panel line

D.A. Maisano†, M. Trombini and A. Pagani
*Politecnico di Torino,*
*Corso Duca degli Abruzzi 24, Turin, 10129, Italy*
†*E-mail: domenico.maisano@polito.it*

Constructing cruise-ship hull is complex and requires precise metalwork, welding and assembly. Early anomaly detection and correction are vital for cost and time management. This paper presents a novel *statistical quality control* (SQC) methodology for monitoring the *panel line* in cruise-ship shipyards, i.e., one of the initial manufacturing workshops, with a relatively high level of automation. The proposed methodology adopts a standardized *p* control chart with samples of variable size, incorporating two elements: (i) it accounts for the high level of customization of panels, and (ii) it takes into consideration the measurement uncertainty associated with the *large-volume metrology* instrument employed for conformity verification (such as a state-of-the-art total station), following the ISO 14253-1:2017 standard. A real-world case study demonstrates its practical application.

*Keywords*: shipbuilding; cruise-ship hull; panel line; conformity verification; ISO 14253-1:2017; large-volume metrology; total station; standardized *p*-chart.

## 1. Introduction

Cruise-ship hull construction involves multiple operations on large metal parts, divided into four phases: (i) preparation of *panels* by cutting, shaping, bending, and joining plates to rigid elements, (ii) assembly of panels to make *units* with dimensions around (20–40 m) × (20–40 m) × (3–5 m), (iii) stacking of two or three units to make *modules*, and (iv) final assembly of modules to erect the complete hull [1]. This process is challenging due to several factors, such as [2]:

(i) The large size and the relatively high level of customization of the parts manufactured complicate the organization of the production process and supply chain.
(ii) The unpredictable sequence of operations, due to the availability of a large number of operators, equipment and the *rework* that becomes systematically necessary.
(iii) The inevitable presence of deviations from the nominal design dimensions, which can lead to nonconformities.

Nonconformities, if not detected and corrected in time, can lead to significant additional costs, especially in the final stages of the process. In some cases, they can even alter the structural aspects of the ship or generate aesthetic anomalies [1]. Dimensional specifications related to the geometry of parts manufactured in cruise-ship shipyards are usually around a few millimetres from nominal (design) values [3, 4].

To prevent the “propagation” of nonconformities, it is important to monitor the production process in real time using *statistical quality control* (SQC) tools. Timely feedback on the conformity of the work performed is highly beneficial, not only to prevent the propagation of errors but also to provide guidance to operators [5]. Traditional SQC methods are not always suitable for the construction of cruise ships, as (i) they are typically designed for mass production, with a limited level of customisation, and (ii) they do not consider the *measurement uncertainty* of the quality characteristics of interest.

This paper proposes a novel SQC methodology for monitoring the panel line of cruise-ship shipyards. The proposed methodology is based on a standardized *p*-chart that takes into account the measurement uncertainty of the instrument used for conformity verification, in line with the ISO 14253-1:2017 standard, and accommodates the fact that panels can be highly customized [6]. Dimensional verifications are performed through a state-of-the-art instrument for *large-volume metrology* (LVM), namely a Leica Nova TS60 scanning total station equipped with a contact probe [7, 8].

This paper is organized into three sections. The first one contains preliminary information, including a case study from a Fincantieri S.p.A. shipyard, technical instrument details, and ISO 14253-1:2017 standard overview. The second section details the SQC methodology, incorporating ISO 14253-1:2017-based conformity verifications and a standardized *p*-chart, illustrated through the case study. The third section illustrates the practical implications of this research, highlighting the methodology’s potential, limitations, and future research insights.

## 2. Preliminary information

### *Case study*

Let’s delve into the panel line, probably the shipyard’s only automated workshop, in which steel plates (i.e., *panels*) are joined, marked with lines/curves for alignment, cut, and reinforced with longitudinal stiffeners, transverse beams, and longitudinal girders. Panels move rapidly on roller conveyors between various stations, each with brief stationary times. The total throughput time of panels (i.e., from entering to leaving the panel-line workshop) is of the order of a few hours.

The panel line's automation offers flexibility for producing uniquely shaped components efficiently. In addition, ensuring dimensional accuracy is crucial for quality and timely manufacturing. Let's consider the panel line at a Fincantieri S.p.A. shipyard, producing panels for various ships with a dynamic sequence. In this context, quality engineers define several (geometric) quality characteristics to monitor, which may vary across panels. Table 1 provides an example of (geometric) quality characteristics for a specific panel, primarily distances between reference positions, with specifications of ±2 mm around their nominal value. Operators use advanced total stations for verifications.

Table 1. Dimensional verifications for a specific panel. Thirty-eight quality characteristics (i.e., distances between reference positions on the panel surface) are verified using a Leica Nova TS60 scanning total station (with standard uncertainty $u \approx 0.45$ mm). Conformity verification follows ISO 14253-1:2017, with a guard band of $g \approx 0.74$ mm around each specification limit. "Δ" indicates deviation from the nominal value. Symbols "✓", "✗", and "?(✓)" represent undoubted conformity, undoubted nonconformity and dubious conformity, respectively.

| Qual. characteristic no. | Specifications [mm] | | | $y$ [mm] | $\Delta = y - NV$ [mm] | Conforming? |
|---|---|---|---|---|---|---|
| | $NV$ | $LSL$ | $USL$ | | | |
| 1 | 2500 | 2498 | 2502 | 2500.7 | 0.7 | ✓ |
| 2 | 2740 | 2738 | 2742 | 2738.7 | -1.3 | ?(✓) |
| 3 | 13460 | 13458 | 13462 | 13459.9 | -0.1 | ✓ |
| 4 | 9410 | 9408 | 9412 | 9408.9 | -1.1 | ✓ |
| 5 | 11510 | 11508 | 11512 | 11509.6 | -0.4 | ✓ |
| 6 | 5120 | 5118 | 5122 | 5116.8 | -3.2 | ✗ |
| 7 | 16240 | 16238 | 16242 | 16238.0 | -2.0 | ?(✓) |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 36 | 3180 | 3178 | 3182 | 3180.1 | 0.1 | ✓ |
| 37 | 10940 | 10938 | 10942 | 10940.0 | 0.0 | ✓ |
| 38 | 14990 | 14988 | 14992 | 14993.0 | 3.0 | ✗ |

### *LVM instrument*

In recent decades, shipyard measuring tools have evolved from traditional equipment (e.g., plumb bobs, steel tapes and transits) to advanced LVM instruments, like laser scanners, trackers, and total stations equipped with contact/non-contact probes, which enable the rapid acquisition of 3D data for surface reconstruction [7].

For panel-line inspections, modern total stations with contact probe accessories offer a practical balance of convenience and precision [8]. In our case study, we used the Leica Nova TS60 scanning total station with a "mini-vector" probe [9]. The instrument's performance was assessed, yielding a conservative $u \approx 0.45$ mm standard uncertainty in single distance measurements.

***ISO 14253-1:2017 standard***

ISO 14253-1:2017, part of the GPS standards family, can be used to verify conformity with quality-characteristic specifications while considering measurement uncertainty [6]. Verification is sensitive near lower and upper specification limits (i.e., LSL and USL), with the risk of resulting in *false nonconformings* (i.e., real conforming items that are misclassified as nonconforming ones) or *false conformings* (i.e., real nonconforming items that are misclassified as conforming ones). Figure 1 shows doubt in conformity or nonconformity verification outside or inside the specification range; this doubt arises in the "?" zones around specification limits, requiring the application of a suitable decision rule.

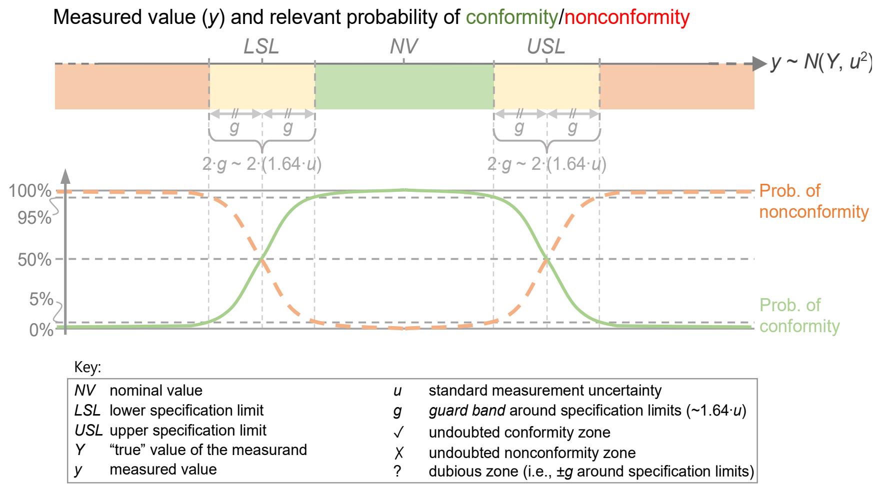


Fig. 1. Conformity verification according to ISO 14253-1:2017, based on (i) the measurement result ($y$) of a quality characteristic of interest and (ii) the decision rule adopted.

ISO 14253-1:2017 offers two decision rules, depending on whether the need to limit the risk of false nonconformings (e.g., to limit unnecessary repair work) or the risk of false conformings prevails (e.g., to prevent potential failures). Rule #1 bilaterally extends the conformity range of the specification limits by a guard band of semi-width $g$ (i.e., conformity range equal to zone "✓" plus zone "?", in Fig. 1), while Rule #2 bilaterally narrows it by the same amount (i.e., conformity range equal to zone "✓" only). When the standard uncertainty ($u$) is ¼ of the specification interval (USL – LSL) or less, a $g \approx 1.64 \cdot u$ guard band maintains risks (of false nonconfirmings and false conformings) below 5% for both rules (see Fig. 1) [6].

## 3. SQC methodology

### *Control chart selection*

Selecting a control chart for monitoring the shipyard panel line should consider its unique characteristics: fast panel transition, high customization, and diverse conformity verifications (in type and number). The standardized *p* control chart for attributes is chosen, for which each panel represents an *i*th sample with variable quality characteristics, assessed against specifications [6]. For example, Table 1 shows an *i*th sample (panel) with $n_i = 38$ quality characteristics, verified using the Leica Nova TS60 scanning total station. Verifications are done collectively at the panel line exit, and each quality characteristic is marked as conforming ("✓") or nonconforming ("✗"). The total number of defectives ($d_i \in [0, n_i]$) and the panel defectiveness ($p_i = d_i/n_i \in [0, 1]$) can then be calculated for the *i*th specific panel.

The verification of different quality characteristics and the determination of an overall panel-by-panel defectiveness ($d_i$) are justified when the *natural variability* among quality characteristics is relatively homogeneous, specification ranges are similar (e.g., ±2 mm around nominal values), and measurement uncertainty for the different measurements is comparable. In this case study, these conditions are met.

### *Construction of the standardized p control chart*

The construction of the standardized *p* control chart requires a dataset of at least 15–20 samples (i.e., panels) of no less than 20–25 elements (i.e., quality characteristics) each. In the case study, 21 panels were used, each with different quality characteristics (in number and type). The fact that the measurement uncertainty ($u \approx 0.45$ mm, cf. Sec. 2) is not negligible compared to the specification interval (i.e., to be negligible it should be at least one order of magnitude lower) leads to the adoption of ISO 14253-1:2017, with rule #1 chosen for the specific case of interest. Quality characteristics classified as conforming are further categorized as undoubtedly conforming (in case the measurement result falls in the "✓" zone) or doubtfully conforming (in case the measurement result falls in the "?(✓)" zone) (cf. Fig. 1).

Table 1 (in the last column) exemplifies the outcome of some conformity verifications for the specific panel no. 1, revealing $d_1 = 6$ nonconforming quality characteristics out of $n_1$ = 38, resulting in a sample defectiveness of $p_1$ = 6/38 ≈ 15.8%. Among the 32 conforming quality characteristics, half are undoubtedly conforming ("✓"), and half are doubtfully conforming ("?(✓)"). Extending these verifications to the remaining 20 panels generates the data in Table 2. The number of defectives ($d_i$) in an $i$th panel with $n_i$ quality characteristics follows a binomial distribution, with mean $\mu_d$ and variance $\sigma_d^2$. Based on available data, the best estimate of the defectiveness ($p$) of the whole panel-line process is [5]:

$$\bar{p} = \frac{\sum_{i=1}^{21} d_i}{\sum_{i=1}^{21} n_i} \approx 14.2\%. \tag{1}$$

Table 2. Data for constructing the standardized $p$ control chart, including the calculation of $\bar{p}$, i.e., the best estimate of $p$ based on available data.

| Sample (panel) no. | $n_i$ | $d_i$ | $p_i$ | $z_i$ |
|---|---|---|---|---|
| 1 | 38 | 6 | 15.8% | 0.280 |
| 2 | 39 | 6 | 15.4% | 0.212 |
| 3 | 35 | 8 | 22.9% | 1.467 |
| 4 | 35 | 7 | 20.0% | 0.983 |
| 5 | 46 | 6 | 13.0% | -0.225 |
| 6 | 37 | 4 | 10.8% | -0.591 |
| 7 | 45 | 7 | 15.6% | 0.260 |
| 8 | 38 | 5 | 13.2% | -0.184 |
| 9 | 44 | 6 | 13.6% | -0.107 |
| 10 | 44 | 3 | 6.8% | -1.403 |
| 11 | 35 | 7 | 20.0% | 0.983 |
| 12 | 43 | 8 | 18.6% | 0.827 |
| 13 | 40 | 3 | 7.5% | -1.214 |
| 14 | 44 | 9 | 20.5% | 1.188 |
| 15 | 36 | 9 | 25.0% | 1.856 |
| 16 | 47 | 9 | 19.1% | 0.972 |
| 17 | 41 | 4 | 9.8% | -0.816 |
| 18 | 37 | 2 | 5.4% | -1.533 |
| 19 | 42 | 3 | 7.1% | -1.311 |
| 20 | 40 | 6 | 15.0% | 0.145 |
| 21 | 46 | 3 | 6.5% | -1.492 |
| | $\sum_{i=1}^{m} n_i = 852$ | $\sum_{i=1}^{m} d_i = 121$ | $\bar{p} = 14.2\%$ | |

If $n_i \cdot p_i \geq 5$, the binomial distribution of $d_i$ can be approximated by a normal distribution with the same parameters [5]. Since $p_i$ is linearly related to $d_i$ (with $n_i$ considered constant for an individual $i$th panel), it can also be approximated by a normal distribution with identical parameters (i.e., $\mu_p = p, \sigma_p = \sqrt{\frac{p\cdot(1-p)}{n_i}}$). In addition, a standardisation of $p_i$ values can be introduced by means of the transformation:

$$z_i = \frac{p_i - p}{\sigma_p} = \frac{p_i - p}{\sqrt{\frac{p \cdot (1-p)}{n_i}}}, \quad (2)$$

$z$ being the standard normal variable with zero mean and unit variance.

Table 2 displays $d_i$, $p_i$, and $z_i$ values for each $i$th sample. Except for isolated cases (samples 3, 4, and 11), the condition $n_i \cdot p_i \geq 5$, which is necessary for approximating $d_i$ and $p_i$ as normally distributed variables, is consistently met [5, 10].

Figure 2 presents the standardized $p$-chart with $z_i$ values from Table 2, along with three-sigma control limits ($UCL = 3$, $CL = 0$, and $LCL = -3$); three-sigma limits are commonly used in SQC because they offer a good compromise between responsiveness in detecting anomalies and reducing the risk of false alarms [5]. All data points fall within control limits, displaying a seemingly random pattern. This randomness is statistically confirmed through the traditional Western Electric rules and the Anderson-Darling normality test [5, 10]. Therefore, this control chart effectively monitors the process under stable conditions, free from "assignable" sources of variability, and can be used to monitor future process evolution.

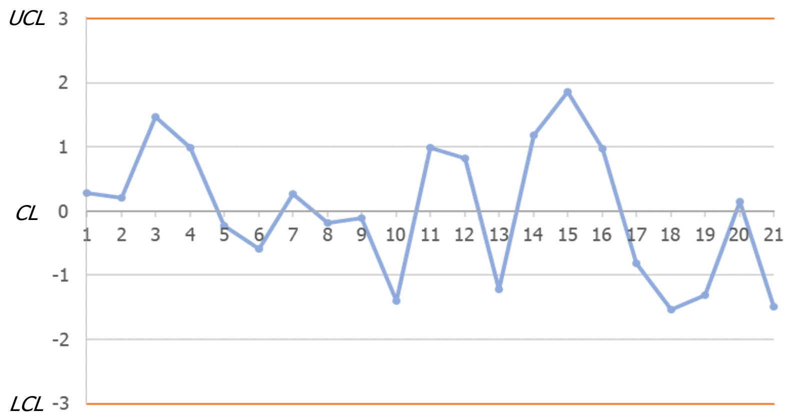


Fig. 2. Standardized $p$-chart related to the $z_i$ values in Table 2.

## 4. Discussion

The proposed methodology is valuable for overseeing manufacturing operations in the shipyard's panel line, operating at two intertwined levels:

*Product Conformity Verification* This activity aims at promptly identifying anomalies in manufactured products, enabling corrective actions to limit error propagation and excessive repair work in final assembly. An innovative aspect is handling the measurement uncertainty through ISO 14253-1:2017, allowing the distinction between undoubted cases of conformity/nonconformity and doubtful cases, in which measured values fall in the guard band around specification limits. Undoubted nonconformities demand immediate action, while doubtful cases can be documented for cautious handling in subsequent stages; for instance, measurements could be reinforced around the area of concern and/or more precise instruments might be employed. The approach also provides flexibility, allowing quality managers to choose the most suitable decision rule. Although in the case study at a Fincantieri S.p.A. shipyard's panel line, a Leica Nova TS60 total station was used for conformity verifications, this method can adapt to other LVM instruments.

*Process Stability Monitoring* The standardized *p*-chart makes it possible to continuously monitor the manufacturing process, identifying steady progress or potential disturbances from abnormal factors requiring investigation. Any out-of-control situation detected by the control chart prompts investigations into root causes. For instance, increased panel defectiveness may stem from processing errors (human-induced or machinery/material-related), while reduced defectiveness could result from errors or deliberate manipulation of conformity verification by operators [5]. The standardized *p*-chart is straightforward to create and manage, with variables $d_i$, $n_i$, and $p_i$ having practical meanings for non-statisticians. However, interpreting $z_i$ requires basic statistical knowledge [5, 10].

The proposed methodology has some limitations. It assumes that conformity verifications pertain to quality characteristics with reasonably similar defectiveness rates; otherwise, the control chart model becomes more complex [5, 10]. Defining the specific quality characteristics for each panel is delicate, as they should constitute an adequate number of features that are representative of the process quality, without redundancy. Expertise from quality engineers is crucial. Additionally, all conformity verifications for a panel condense into a single data point, making the control chart not very responsive to gradual process shifts, which typically require multiple data points for detection.

## References


1. Mandal N.R. (1989) *Ship construction and welding*, Vol. 329, Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping 2. Singapore: Springer.
2. Bay M., Crama Y., Langer Y. *et al.* (2010) Space and time allocation in a shipyard assembly hall. *Annals of Operations Research*, 179(1): 57–76.

3. Storch R.L. and Giesy P.J. (1998) The use of computer simulation of merged variation to predict rework levels on ship's hull blocks. *Journal of ship production*, 4(03): 155–168.
4. ISO 15583:2005. Ships and marine technology — Maritime standards list, International Organization for Standardization, 2005, https://www.iso.org/standard/36696.html.
5. Montgomery D.C. (2019) *Introduction to statistical quality control* (8th edition), John Wiley & Sons.
6. ISO 14253-1:2017 (2017) *Geometrical product specifications (GPS) – Inspection by measurement of workpieces and measuring equipment – Part 1: Decision rules for verifying conformity or nonconformity with specifications*.
7. Franceschini F., Galetto M., Maisano D. *et al.* (2011) *Distributed large-scale dimensional metrology: new insights*. Springer Science & Business Media, London.
8. Maisano D.A., Mastrogiacomo L., Franceschini F. *et al.* (2023) Dimensional measurements in the shipbuilding industry: on-site comparison of a state-of-the-art laser tracker, total station and laser scanner. *Production Engineering*, 17(3–4): 625–642.
9. Hexagon Geosystems (2023) Leica Nova TS60 Totla Station. Available online: https://leica-geosystems.com/it-it/products/total-stations/robotic-total-stations/leica-nova-ts60.
10. Ross S.M. (2020) *Introduction to probability and statistics for engineers and scientists* (6th edition). Academic press (Elsevier).