Original Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING MANUFACTURE

Proc IMechE Part B: J Engineering Manufacture
1–13

DOI: 10.1177/09544054241235742
journals.sagepub.com/home/pib
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A new statistical-quality-control methodology for panel line monitoring in shipyards

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Abstract

The construction of cruise ship hulls is a complex process that involves various stages: it begins with the fabrication of panels, which involves marking, cutting, and shaping metal plates of considerable length, followed by the welding of rigid structural components onto these panels. To minimize delays and cost overruns, it is crucial to detect any anomalies early on and rectify them through appropriate repair work. Therefore, real-time conformity verifications and effective *Statistical Quality Control* (SQC) methodologies are necessary. This paper proposes a novel SQC methodology, specifically tailored for monitoring the panel line in cruise-ship shipyards. This methodology, while adopting a traditional standardized *p* control chart with samples of variable size, integrates two original aspects: (i) it accounts for the significant level of customization and specific quality characteristics inherent in the different panels and (ii) it rigorously considers the measurement uncertainty associated with the large-volume metrology instruments (such as state-of-the-art total stations, laser trackers or laser scanners) used for conformity verification, following the ISO 14253-1:2017 standard. The methodology is exemplified through a real-world case study, providing practical insights into its application.

Keywords

Shipbuilding, cruise-ship hull, panel line, statistical quality control, conformity verification, ISO 14253-1:2017, large-volume metrology, total station, standardized *p*-chart

Date received: 26 September 2023; accepted: 11 February 2024

Introduction

The construction of cruise-ship hulls is a complex manufacturing process with multiple operations on large metal plates.[1] This process can be divided into four macro-phases[2–4]:

1. Preparation of *panels* by cutting, shaping, bending, and joining plates to rigid elements, such as beams, girders, or other reinforcing structures. The specific shipyard's workshop where these operations take place is called the *panel line*.
2. Assembly of panels to make *units* with dimensions around (20–40 m) × (20–40 m) × (3–5 m).
3. Assembly of units to make *modules* with dimensions around (20–40 m) × (20–40 m) × (6–12 m), by joining at least two units.
4. Final assembly of modules to erect the complete hull, either in a dry dock or slipway.

One element of complexity in the hull-construction process is the large size of the parts being manufactured. The process can be classified as *engineer to order* as it makes highly customized products on a very small series basis, for example, each ship design usually involves the production of no more than three to five pieces.[5] Some shipyards, including those of Italy's Fincantieri S.p.A., rely heavily on the high degree of customization of cruise ships as a competitive lever to survive against fiercer competitors.[6] However, this leads to greater complexity in organizing the production

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process and the relevant supply chain.[7] The sequence of operations is often unpredictable, due to the availability of many operators and equipment, as well as the rework that is systematically required. The macro-phase with the higher incidence of repair work is final assembly, in which all residual anomalies and nonconformities – often generated earlier and not adequately handled up to that point – must forcibly be corrected aboard the structures being worked on.[8]

Like any manufacturing process, hull construction involves inevitable deviations from the nominal design dimensions in the *quality characteristics*[1] of the items being processed. Common deviations include: defects on the surface of plates (finish defects, corrosion, non-metallic inclusions, presence of discontinuities, etc.), unevenness in the thickness of plates, defects in alignment and distance between the elements to be welded (e.g. excessively small gaps can be corrected by removal of excess material, while excessively large gaps can be corrected by welding "strips" of material),[9] and residual stresses/strains resulting from clamping and welding operations (due to so-called "shrinkage").[10,11] Possible causes of such deviations can be attributed to imperfections in materials, operator error, and manufacturing problems resulting from poorly maintained equipment, inadequate facilities, poor lighting, an unleveled work area, an ambiguous work instrument, and work parameters that are not easily controlled. For example, some not-easily-controlled parameters of welding operations concern the extent of any preheating/pretensioning of the surfaces involved, the extent of heat input during welding, and the width of the surfaces involved in the process.[12] If detected during production, nonconformities can be corrected through repair/rework, which, however, involves significant additional costs, especially in the final stages of the process.[8] More serious nonconformities can also alter structural aspects – such as strength, stability, and fatigue wear in critical areas of the hull – and contribute to the generation of esthetic anomalies in the ship's interior fittings, such as imperfect surface flatness, presence of "steps," etc.[13] Cracks triggered by prolonged loads and fatigue stresses can occur even after an initial period of ship operation, usually ranging from a few months to 3–4 years.[10]

Imperfections may gradually accumulate in the various manufacturing phases and combine into a sort of "error propagation."[9] In order to limit such propagation within acceptable values – that is, without altering the steady progress of hull construction and functionality of the ship in operation – shipyards have internal *specification* standards, which discriminate between deviations that are *tolerable*, that is, with no significant adverse effects, and deviations that are *intolerable*, that is, those that are potentially detrimental to processing/assembly steps, the functionality of the ship in operation, or esthetics. It is crucial to promptly identify and rectify deviations of the second type to mitigate increasing repair costs and minimize disruptions.[9,14–18] Dimensional specifications related to the geometry of parts manufactured in cruise-ship shipyards are usually around a few millimeters from nominal (design) values.[11] This denotes a certain severity when taking into account the overall dimensions of the whole cruise-ship, which are on the order of several 100 m (implying relative deviations of about 1/100,000).

For production to be lean, efficient and effective, it should be adequately supported by real-time conformity verification and *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. This is particularly important considering that operators may not always have extensive experience due to rapid turnovers in the industry.[2,3] In addition to verifying the conformity of the production output, it is also important to study the *natural variability*[2] of the relevant process. In the presence of anomalies, this variability increases as does the propensity to produce products that do not comply with specifications.[19] However, this does not mean that processes governed exclusively by natural variability cannot generate nonconforming products; in fact, this depends on how stringent the specifications are with respect to the corresponding natural variability.

The present article focuses on the *panel line* of the major cruise-ship shipyards, in which highly customized panels are continuously manufactured. To limit the postponement of repair work in the final assembly, it is important to verify the conformity of the operations through intermediate verifications on the manufactured parts, before their delivery to the next production stages. Verifications typically concern distances between pairs of reference positions, angles or other geometric quality characteristics.

This paper proposes a novel SQC methodology for monitoring the panel line, based on the use of a standardized *p control chart* for attributes.[19] The proposed approach considers the measurement uncertainty of the instrument used for conformity verification, in line with the relatively recent ISO 14253-1:2017 standard, and accommodates the fact that panels can be highly customized.[20] Dimensional verifications are performed through a state-of-the-art instrument for large-volume metrology[3] (LVM), namely a Leica Nova TS60 scanning total station equipped with a contact probe.[4]

The remainder of this article is organized into four sections. Section 2 provides a literature review on the use of control charts, highlighting inherent practices and identifying gaps in SQC within the shipbuilding context. Section 3 contains some preliminary information that may be helpful for understanding the methodology: (i) a description of the operational context in the form of a real-world *case study* within a Fincantieri S.p.A. shipyard, (ii) technical notes on the instrument for dimensional verifications, and (iii) a summary of the ISO 14253-1:2017 standard and the "decision rules" covered therein. Section 4 is the core of the paper and contains a detailed description of the proposed SQC methodology, which incorporates conformity verifications based on ISO 14253-1:2017 and a standardized *p*-chart; the step-by-step construction and use of the control chart is exemplified through the case study. Section 5 discusses the practical implications of the proposed methodology, highlighting its potential, limitations and insights for future research.

Literature review

In the context of shipbuilding, particularly in the construction of cruise-ship hulls, SQC tools can assist in ensuring process efficiency and product quality. Among these tools, *control charts* stand out for their widespread application in monitoring the natural variability of processes across various sectors, including manufacturing, service, and accounting/auditing. These tools are crucial for tracking the performance of a process over time, identifying potential anomalies against stable operating conditions, and facilitating timely corrective actions.[10,19,21]

The application of control charts within the specific domain of hull construction in shipbuilding has been explored in the scientific literature.[22] Notable examples include the use of control charts for variables ($\bar{x}$ and R) to monitor the marking and cutting operations at the panel line.[9,19] Similar methodologies are employed for monitoring the thickness of plates,[11] the geometry of structural reinforcing bars,[10] and the efficiency of welding operations.[8] Furthermore, Chung[13] presented the application of control charts for attributes in pipeline installation. However, these applications predominantly rely on organizing parts into samples of fixed size, which proves to be less effective in the context of highly customized short-run productions, where the quality characteristics of interest may vary significantly from part to part.[23] In addition, a common shortfall in these studies is the omission to consider measurement uncertainty, which is a crucial factor when assessing quality characteristics and an issue that extends beyond shipyard applications to other operational contexts.[19]

In response to these identified gaps, this work proposes an innovative methodology that addresses two key challenges: (i) it effectively adapts to the high level of customization and the diverse quality characteristics encountered across different panels and (ii) it rigorously incorporates the measurement uncertainty associated with the use of large-volume metrology instruments for conformity verification.

Preliminary information

This section is organized in three subsections concerning respectively: the presentation of the case study, the LVM tool used in it, and some references to ISO 14253-1:2017 standard.

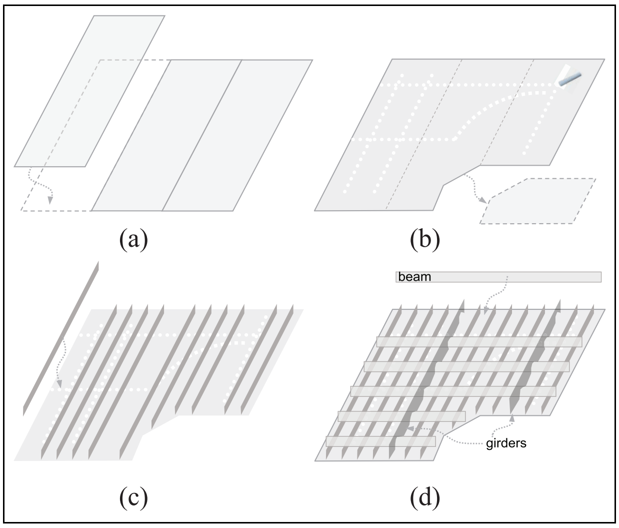

Figure 1. Panel line operations in a shipyard, showing panels in an upside-down orientation compared to their final placement in the ship. The ship's longitudinal axis is aligned with the longitudinal stiffeners and girders: (a) joining and welding of plates, (b) marking and cutting, (c) welding of longitudinal stiffeners, and (d) welding of beams/girders.

Real-world case study

Let us focus on the panel line, which is one of the very few shipyard workshops where a significant portion of the work is automated. Figure 1 schematizes a typical panel-line processing. The plates are first joined and then marked by imprinting lines/curves on their surface, which serve as references for subsequent alignment and assembly of additional elements. Subsequently, the plates are cut and reinforced through welding, which involves attaching longitudinal stiffeners, transverse beams – often simply referred to as "beams"– as well as longitudinal beams, commonly referred to as "girders." The processing of the plates is relatively swift, occurring via large roller conveyors that feature multiple stations dedicated to various operations. The stationary time at each station is typically just a few dozen minutes. Figure 2 illustrates the aerial view of the panel lines of two different shipyards, where the total throughput time of plates (i.e. from entering to leaving the panel-line workshop) is in the order of a few hours.

Thanks to its automated stations, the panel line is a relatively flexible workshop that allows parts with peculiar geometric/structural characteristics to be produced relatively quickly. Since dimensional conformity may affect the quality and on-time performance of various manufacturing operations, it should be constantly monitored. Let us consider the panel line of a major Fincantieri S.p.A. shipyard, where various panels – often intended for the construction of different ships – are produced sequentially. The sequence of panel arrivals is not rigid and can often be varied at the last minute, depending on contingent requirements. For each

Figure 2. (a) Aerial view of the panel line at Fincantieri S.p.A. shipyard in Monfalcone showing the direction of panel flow from bottom to top (panels not present) and (b) aerial view of the panel line at Fincantieri S.p.A. shipyard in Ancona, with the panel flow moving from left to right.

specific panel, quality engineers typically define several (geometrical) quality characteristics to be monitored. The number and the type of quality characteristics may generally vary from panel to panel.

Table 1 exemplifies a set of (geometrical) quality characteristics for a specific panel,[4] essentially distances between pairs of reference positions. It can be noticed that the lower and upper specification limits (*LSL* and *USL*) are ± 2 mm around their respective nominal or target value (*NV*).[9,18] Verifications are performed by a team of experienced surveyors, using a state-of-the-art total station (see Section 3.2). Figure A1 (in Appendix) exemplifies a technical drawing of a specific panel at a Fincantieri S.p.A. shipyard, depicting the nominal values of several dimensional quality characteristics. Additionally, Figure A2 (in Appendix) exemplifies a form used by inspectors to report the results of dimensional inspections of the quality characteristics of interest. For confidentiality, some of the data are intentionally omitted or altered.

LVM measuring instrument

The last two to three decades have witnessed a relevant evolution of the LVM instruments used in shipyards: from plumb bobs, steel tapes and transits to laser

Table 1. Example of dimensional verifications related to a specific panel. The 38 (geometric) quality characteristics are all distances between pairs of reference positions on the panel surface. Measurements are carried out using a Leica Nova TS60 scanning total station (cf. Section 3.2); y is the measurement result, while $u \approx 0.45$ mm is the standard measurement uncertainty related to each distance measurement. Conformity verifications are carried out according to ISO 14253-1:2017 (cf. Section 3.3); the semi-amplitude of the *guard band* around each specification limit is $g \approx 0.74$ mm. Δ is the (positive or negative) deviation from the nominal value (NV). The symbols "✓," "×," and "?(✓)" denote quality characteristics of *undoubted conformity, undoubted nonconformity*, and *dubious conformity*, respectively (cf. Section 4.2).

Qual. characteristic no.	Specifications [mm]			y [mm]	$\Delta = y - \text{NV}$ [mm]	Conforming?
	NV	LSL	USL			
1	2500	2498	2502	2500.7	0.7	✓
2	2740	2738	2742	2738.7	−1.3	?(✓)
3	13,460	13,458	13,462	13,459.9	−0.1	✓
4	9410	9408	9412	9408.9	−1.1	✓
5	11,510	11,508	11,512	11,509.6	−0.4	✓
6	5120	5118	5122	5116.8	−3.2	×
7	16,240	16,238	16,242	16,238.0	−2.0	?(✓)
8	10,980	10,978	10,982	10,979.6	−0.4	✓
9	15,190	15,188	15,192	15,186.5	−3.5	×
10	10,370	10,368	10,372	10,370.0	0.0	✓
11	3580	3578	3582	3579.6	−0.4	✓
12	5970	5968	5972	5972.0	2.0	?(✓)
13	3130	3128	3132	3131.5	1.5	?(✓)
14	7550	7548	7552	7549.3	−0.7	✓
15	12,630	12,628	12,632	12,631.4	1.4	?(✓)
16	7260	7258	7262	7258.0	−2.0	?(✓)
17	10,070	10,068	10,072	10,067.8	−2.2	?(✓)
18	13,550	13,548	13,552	13,548.3	−1.7	?(✓)
19	4630	4628	4632	4628.7	−1.3	?(✓)
20	8520	8518	8522	8519.2	−0.8	✓
21	5380	5378	5382	5378.1	−1.9	?(✓)
22	8200	8198	8202	8200.7	0.7	✓
23	6440	6438	6442	6436.6	−3.4	×
24	8140	8138	8142	8136.5	−3.5	×
25	15,170	15,168	15,172	15,167.8	−2.2	?(✓)
26	12,630	12,628	12,632	12,628.6	−1.4	?(✓)
27	3460	3458	3462	3460.0	0.0	✓
28	16,110	16,108	16,112	16,110.3	0.3	✓
29	14,430	14,428	14,432	14,430.1	0.1	✓
30	12,150	12,148	12,152	12,151.8	1.8	?(✓)
31	5770	5768	5772	5770.9	0.9	✓
32	9660	9658	9662	9657.2	−2.8	×
33	10,850	10,848	10,852	10,852.3	2.3	?(✓)
34	8640	8638	8642	8641.4	1.4	?(✓)
35	7710	7708	7712	7712.0	2.0	?(✓)
36	3180	3178	3182	3180.1	0.1	✓
37	10,940	10,938	10,942	10,940.0	0.0	✓
38	14,990	14,988	14,992	14,993.0	3.0	×

scanners, laser trackers, and total stations equipped with contact probes and/or scanning systems.[4] State-of-the-art instruments enable quick acquisition of large amounts of 3D points for the reconstruction of complex surfaces.

For dimensional inspections in the panel-line shop, a good compromise between measurement practicality and accuracy can be achieved with the latest generation of total stations, using contact probe accessories to reach the points of interest.[4] Figure 3 shows the LVM instrument used for dimensional verifications in the case study: a Leica Nova TS60 scanning total station equipped with a *mini-vector* probe.[24] The metrological performance of this instrument was experimentally

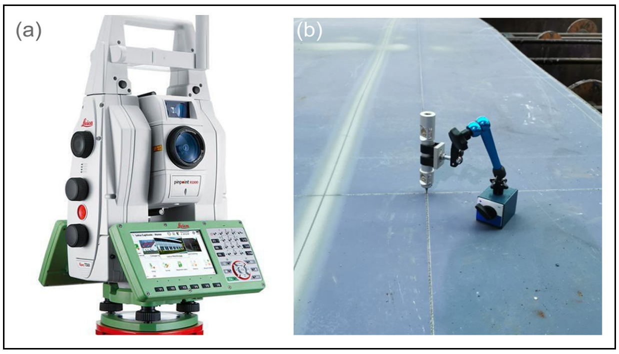

Figure 3. Measuring instrument and accessory in use: (a) Leica Nova TS60 scanning total station with (b) *mini-vector* contact probe accessory.

evaluated under relatively unfavorable shipyard conditions, with air currents, thermal gradients, vibrations, sudden bright flashes, etc.[4] It can be conservatively assumed that the *standard uncertainty* associated with a measurement of a single distance is $u \approx 0.45$ mm.[5]

ISO 14253-1:2017 standard

This standard, which is part of the geometric-product-specification (GPS) family, addresses the problem of verifying the conformity with specifications for a quality characteristic, rigorously considering the measurement uncertainty.[20] Verification is particularly delicate in case the measured value falls close to the *LSL* or *USL*, giving rise to two possible risks: (1) the risk of *false nonconformings*, that is, real conforming items that are misclassified as nonconforming ones, and (2) the risk of *false conformings*, that is, real nonconforming items that are misclassified as conforming ones.

The scheme in Figure 4(a) shows that the conformity verification is undoubted when the measurement result (y) is widely within specification limits (i.e. probability of conformity ≈ 100% in the zone marked with "✓"), and the nonconformity verification is undoubted when y is far outside the specification range (i.e. probability of conformity ≈ 0% in the area marked with "×"). However, there are dubious cases when y falls in the two areas marked with "?" around specification limits, known as the *guard bands* with a semi-amplitude of g; these are described in detail below. A so-called *decision rule* to handle the dubious cases should be adopted by mutual agreement of the parties involved (typically, supplier and customer of the product to be verified).[25]

Similar to the U.S. standard ASME B89.7.3.1-2001, ISO 14253-1:2017 contemplates two alternative decision rules, depending on whether the need to limit the risk of false nonconformings or the risk of false conformings prevails.[26,27] In some cases it might a priority to limit the risk of false nonconformings, so as not to run into additional inspection, undue repair work or unfair penalties for suppliers[28]; in other cases, it might be a priority to limit the risk of false conformings, for example, in the assembly of aircrafts, machinery with high masses/powers involved, military instrumentation, or other sensitive contexts where potential failures must be warded off.

Figure 4(b) and (c) schematize the two decision rules contemplated by ISO 14253-1:2017. According to rule #1, aimed at limiting the risk of false nonconformity, the "effective" conformity range is extended with respect to the specification limits by a so-called *guard band* of semi-amplitude g, which depends on the measurement uncertainty; according to rule #2, aimed at limiting the risk of false conformity, the "effective" conformity range is reduced by a similar amount.[20]

In the relatively common case where the standard measurement uncertainty (u) is relatively small compared to the specification interval[6], assuming that the

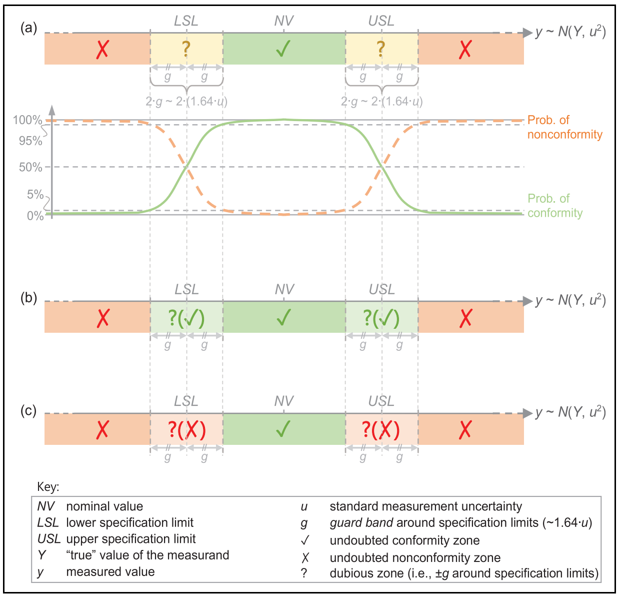

Figure 4. Conformity verification according to ISO 14253-1:2017, based on the result of the measurement (y) of a quality characteristic of interest and the decision rule adopted: (a) measured value (y) and relevant probability of conformity/nonconformity, (b) decision rule #1: nonconformity verification, and (c) decision rule #2: conformity verification. NV: nominal value; LSL: lower specification limit; USL: upper specification limit; Y: "true" value of the measured; y: measured value; u: standard measurement uncertainty; g: *guard band* around specification limits ($\sim 1.64 \cdot u$); ✓: undoubted conformity zone; ×: undoubted nonconformity zone; ?: dubious zone (i.e. $\pm g$ around specification limits).

measurement result (y) is approximately normally distributed with mean equal to the "true" value of the measurand (Y) and variance equal to u^2– that is, $y \sim N(Y, u^2)$– it is customary to define a guard band of semi-amplitude:

$$g = z_{95\%} \cdot u = \Phi^{-1}(95\%) \cdot u \approx 1.64 \cdot u, \qquad (1)$$

$z_{95\%}$ being the 95th percentile of the standard normal variable with zero mean and unit variance,that is,, $z \sim N[0, 1]$, and $\Phi(\cdot)$ being the corresponding cumulative probability density function. The g value in equation (1) ensures that both (i) the risk of false nonconformings when adopting decision rule #1 and (ii) the risk of false conformings when adopting decision rule #2 are systematically lower than $(1-95\%) = 5\%$[7] (cf. Figure 4(a)).[20,25] ISO 14253-1:2017 contains precise guidance on calculating the g-amplitude under general conditions, even when u cannot be considered as relatively small compared to the specification range.[20]

SQC methodology

This section is organized into two subsections concerning respectively: the choice of a suitable control chart and its construction with an application example.

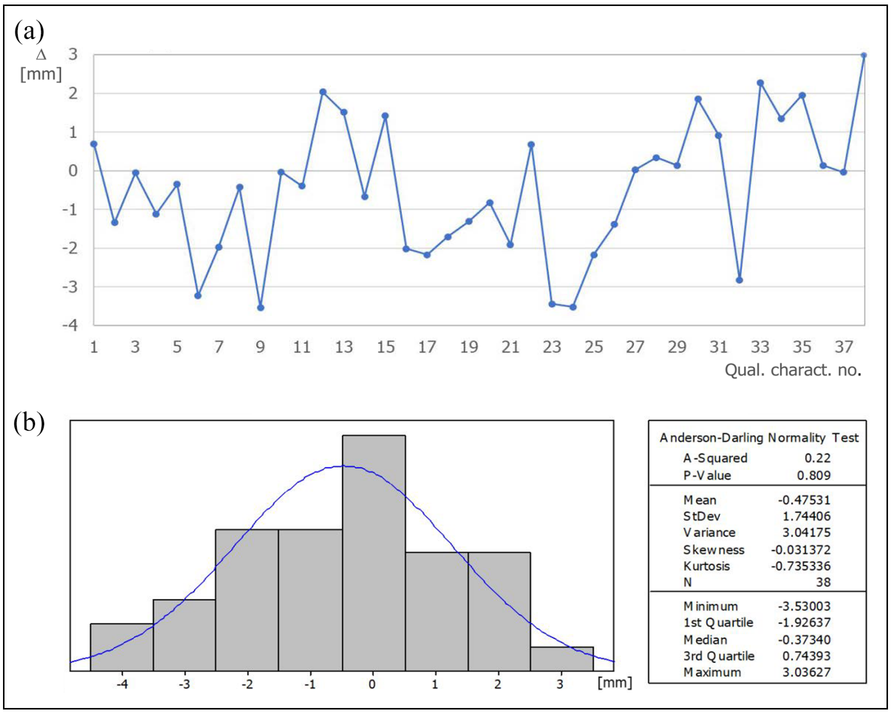

Figure 5. Study of deviations (Δ) between measured values (*y*) and nominal values (*NV*) of the 38 quality characteristics in Table 1. (a) Chronological sequence of Δ values according to the measurements performed and (b) normality test. The analysis was conducted using Minitab® statistical software: (a) deviation of measured value from nominal value → Δ = Y − NV [mm] and (b) histogram of Δ values and normality test.

Choice of the control chart

Choosing a control chart for monitoring a shipyard's panel line requires consideration of three characteristic aspects of this shop: (i) it is relatively quick in terms of transition of the panels being processed, (ii) panels are characterized by a relatively high degree of customization, and (iii) for each (i-th) panel, a number of specific geometrical verifications should be performed (cf. Section 1).

In light of the above considerations, it seems appropriate to adopt a standardized p control chart for attributes, according to which each specific panel is seen as an i-th *sample* of elements of variable numerosity (n_i), consisting of (dimensional) quality characteristics whose conformity to specifications is to be verified[8].[19] For example, the panel exemplified in Table 1 can be viewed as a generic (i-th) sample consisting of $n_i = 38$ quality characteristics, whose conformity to specifications is to be verified using the measuring instrument described in Section 3.2. Although the panel line has several stations with intermediate operations, for convenience and time-saving reasons, verifications are carried out at once at the exit of the panel line itself. After verification, each quality characteristic is classified as conforming ("✓") or nonconforming ("×"). Then the total number of defectives is computed ($d_i \in [0, n_i]$) and the relative *panel fraction conforming*, or *panel defectiveness*, can be determined as: $p_i = \frac{d_i}{n_i} \in [0, 1]$.[19]

Verifying the conformity of different quality characteristics and determining an overall panel-by-panel defectiveness (p_i) is justified when: (i) the natural variability of the different quality characteristics is relatively homogeneous (e.g. in terms of deviations from nominal values), (ii) the specification ranges of the quality characteristics are homogeneous, and (iii) the quality characteristics are measured with the same measurement uncertainty, at least to a first approximation. In the case study, the above conditions are all reasonably satisfied. In particular, Figure 5 shows that – for the quality characteristics of the panel exemplified – process variability is relatively homogeneous in terms of deviations (Δ) from nominal values.[29] Additionally, Figure 5(a) shows a certain homogeneity of the Δ values, which can be approximated as realizations of a normally distributed random variable, while Figure 5(b) shows the result of a corresponding normality test.

Construction of the standardized p control chart

Like any control chart for attributes, the standardized p-chart needs a suitable dataset for construction, consisting of at least 15–20 samples of no less than 20–25 elements each.[19] Returning to the case study in Section 3.1, a dataset of $m = 21$ total panels (i.e. samples) was considered, each consisting of a few dozen quality characteristics to be verified for conformity; the number of quality characteristics (n_i) of course can vary from sample to sample.

Conformity verification deserves special attention since the standard uncertainty of the measurement (i.e. $u \approx 0.45$ mm for the Leica Nova TS60 total station, as shown in Section 3.2) is not negligible compared to the typical specification intervals (i.e. about ± 2 mm around the nominal values). ISO 14253-1:2017 can therefore be applied by choosing an appropriate decision rule (i.e. rule #1 or rule #2, cf. Section 3.3), which depends on the policy of the shipyard quality managers and contingent factors (e.g. any concerns about the quality of materials, workmanship, available time, etc.).

In the specific case study, the rule #1 was adopted, since it is more "indulgent" in case of doubtful (non)-conformity. Among the quality characteristics classified as conforming, those of undoubted conformity (i.e. "✓") can be distinguished from those of doubtful conformity ("?(✓)"), as they fall in the guard band around specification limits (cf. Figure 4(b)).

The last column of Table 1 reports the outcome of the conformity verifications performed on the panel exemplified beforehand. Out of $n_i = 38$ dimensional quality characteristics, $d_i = 6$ were found to be nonconforming (with symbol "×"), resulting in a sample defectiveness of $p_i = \frac{6}{38} \approx 15.8\%$. Among the 38–6 = 32 quality characteristics classified as conforming, exactly half (i.e. 16) are *undoubted conforming* (with symbol "✓") and the other half are *doubtful conforming* (with symbol "?(✓)" and measured values within the guard band). Extending the conformity verifications to the remaining $(m - 1) = 20$ panels (samples) yields the results in Table 2.

$$\hat{p} = \bar{p} = 14.2\%$$

The number of defectives (d_i) in a generic i-th panel with n_i quality characteristics can be modeled as a (discrete) binomially distributed random variable with mean $< \mu_d$ and variance σ_d^2:

$$d_i \sim B\left[\mu_d = n_i \cdot p,\ \sigma_d^2 = n_i \cdot p \cdot (1-p)\right],\quad d_i \in [0, n_i], \qquad (2)$$

where p represents the (unknown) defectiveness of the general hypothetical population of manufactured panels. Based on the available information, the best estimate of p is:

$$\hat{p} = \bar{p} = \frac{\sum_{i=1}^{m} d_i}{\sum_{i=1}^{m} n_i} = \frac{\sum_{i=1}^{m} n_i \cdot p_i}{\sum_{i=1}^{m} n_i} = 14.2\%, \hat{p} \in [0, 1], \qquad (3)$$

m being the number of panels (samples) analyzed (in the example $m = 21$).

Table 2. Data used to construct the standardized p control chart. The lower part of the table includes the calculation of $\bar{p}$, which represents the best estimate of p based on the available information.

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
	$\sum_{i=1}^{m} n_i = 852$	$\sum_{i=1}^{m} d_i = 121$		

If the product $n_i \cdot p_i$ is sufficiently large (i.e. $n_i \cdot p_i \geqslant 5$), the binomial distribution of d_i can be approximated by a (continuous) normal distribution, with same parameters[29]:

$$d_i \sim N\left[\mu_d = n_i \cdot p,\ \ \sigma_d^2 = n_i \cdot p \cdot (1-p)\right],\quad d_i \in [0, n_i]. \qquad (4)$$

As anticipated, the i-th sample defectiveness is defined as:

$$p_i = \frac{d_i}{n_i},\ \in [0, 1]. \qquad (5)$$

Since p_i is linearly related to d_i (i.e. from the perspective of a single i-th panel, n_i can be regarded as constant), it may also be approximated by a normal distribution with the following parameters[29]:

$$p_i \sim N\left[\mu_p = p,\ \ \sigma_p^2 = \frac{p \cdot (1-p)}{n_i}\right],\quad p_i \in [0, 1]. \qquad (6)$$

It can be noticed that the variance of p_i (equation (5)) depends on the sample size n_i; this complicates the construction of the relevant control chart's limits.[19] The scientific literature traditionally overcomes this obstacle by introducing a standardization of p_i:

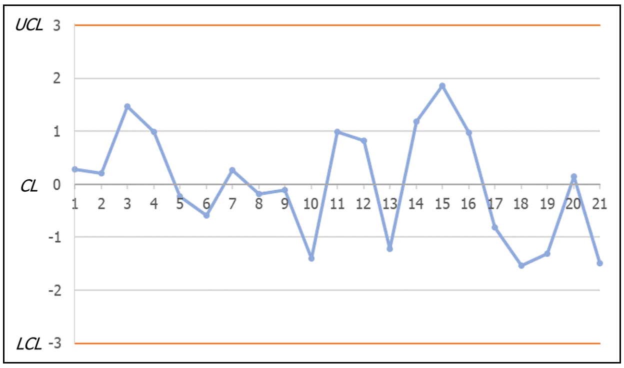

Figure 6. Standardized p-chart related to the z_i values in Table 2.

$$z_i = \frac{p_i - \mu_p}{\sigma_p} = \frac{p_i - p}{\sqrt{\frac{p \cdot (1-p)}{n_i}}}, \tag{7}$$

$z \sim N[\mu_z = 0, \sigma_z^2 = 1]$ being the standard normal variable with zero mean and unit variance.

Table 2 reports the values of d_i, p_i, and z_i for each i-th sample. With the exception of a few sporadic cases (i.e. samples 3, 4, and 11), the condition $n_i \cdot p \geqslant 5$, which is necessary to approximate d_i and p_i to normally distributed variables (cf. equations (4) and (6)), is generally satisfied.[9] This makes the proposed standardization statistically plausible.[19,29]

Figure 6 shows the *standardized p-chart* representing the z_i values in the last column of Table 2, which are plotted over a centerline (CL) and three-sigma control limits (UCL and LCL)[19]:

$$\begin{cases} UCL = \mu_z + 3 \cdot \sigma_z = +3 \\ CL = \mu_z = 0 \\ LCL = \mu_z - 3 \cdot \sigma_z = -3 \end{cases} \tag{8}$$

All points in the control chart are contained within the control limits and the sequence of points seemingly denotes a random pattern; to ascertain this in a statistically rigorous manner, randomness was tested through the traditional *Western Electric rules*.[30] Additionally, Figure 7 shows the application of the Anderson Darling normality test, which fails to reject the hypothesis that the data are normally distributed.[29] Thus, the sequence of points in the control chart can be regarded as random and the parameter $\hat{p} \approx 14.2\%$ (from equation (3)) as representative of the process *natural variability* (cf. Section 1), under stable operating conditions and in the absence of anomalies attributable to so-called "assignable" sources of variability (e.g. machine failures, imperfect materials, or human error).[19,29]

This control chart can therefore be used to monitor the future evolution of the process. For each new panel, the values of d_i, p_i, and z_i can be determined, resulting in an additional point on the control chart. Any points outside the control limits or other non-random patterns can then be monitored with classical randomness tests (e.g. Western Electric rules[30]). Following any changes within the production process (e.g. changes in hardware, operators' work practices, materials, conformity-verification instrumentation and/or decision rule, etc.), the $\hat{p}$ estimate will need to be revised.

Discussion

The methodology proposed in this paper is valuable for monitoring the progress of manufacturing operations in the shipyard's panel line at the two interrelated levels: *product conformity verification* and *process stability monitoring*, as outlined below.

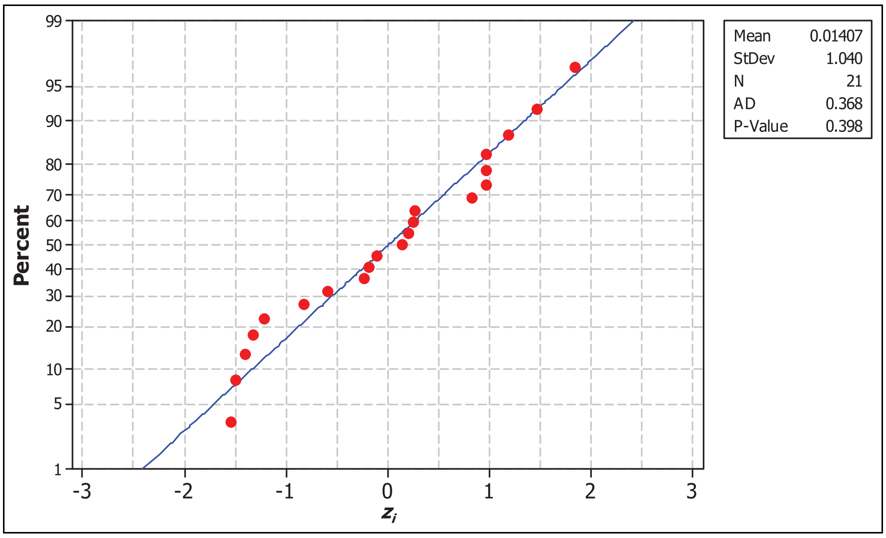

Figure 7. Probability plot and Anderson Darling normality test for the z_i values in Figure 6. The analysis was conducted using Minitab® statistical software.

Product conformity verification

This activity aims to identify possible anomalies in manufactured products to enable prompt corrective actions, with the dual purpose of limiting the "error propagation" and reducing the overload of repair interventions in the final assembly. A novel element is the metrological rigor in managing measurement uncertainty in accordance with ISO 14253-1:2017, which enables the distinction between cases of undoubted conformity/nonconformity and those (doubtful) cases where measured values fall within the guard band around specification limits. Cases of undoubted nonconformity necessitate immediate corrective action, while doubtful cases can be reported and managed with additional caution in subsequent processing steps, assuming a reasonable level of risk. The flexibility of the approach allows quality managers discretion in choosing the most appropriate decision rule, such as minimizing the risk of false conformities while accepting an increased risk of false nonconformities, and *vice versa*. In the case study related to a Fincantieri S.p.A. shipyard's panel line, conformity verifications were conducted using a Leica Nova TS60 total station. However, this methodology can be adapted to other LVM instrument, such as laser trackers and laser scanners.[31]

Process stability monitoring

The application of a standardized *p*-chart facilitates continuous monitoring of the manufacturing process to ensure that it progresses steadily within its expected natural variability. Detection of any *out-of-control* situations by the control chart, such as non-random patterns, should prompt investigations into potential root causes, including operators' errors or anomalies in machinery or input materials.[19] The standardized *p*-chart is user-friendly, as most variables of interest –d_i, n_i, and p_i– are straightforward and easily comprehensible, even for non-statisticians. However, interpreting z_i values requires a basic understanding of statistics.[19]

The proposed methodology has some limitations. Primarily, it presupposes that the conformity verifications involve quality characteristics with similar "natural" defectiveness levels; if this is not the case, adjustments to the control chart model may be necessary.[19] Defining quality characteristics for each specific panel is a critical task as they need to be comprehensive, encompassing geometric/structural characteristics indicative of process quality, and non-redundant, avoiding correlation between characteristics (e.g. two characteristics measuring distances between the same 3D positions should be avoided).[21,29] The expertise of quality engineers is crucial in this aspect. Another limitation is the condensation of all conformity verifications for a panel into a single point on the control chart. This approach may not be sensitive enough to detect gradual process shifts, which generally require multiple data points for detection. This limitation is partially offset by the relatively rapid pace of the online panel process.

Future research should explore the implementation of multivariate control charts. By relaxing some of the simplifying assumptions of the current approach, these charts could facilitate simultaneous monitoring of diverse characteristics with varying natural variabilities, such as geometric features, accuracy in welding operations, and potential residual stress estimations. Plans also include developing tailor-made SQC methodologies for other areas of the shipyard, such as *unit* or *module* processing, which are characterized by slower material flow and higher complexity.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study received partial support from the "SCAFO 4.0" project of the Italian Ministry of Economic Development. Additionally, it was conducted within the framework of the MICS (Made in Italy, Circular and Sustainable) Extended Partnership and received partial funding from the European Union Next-Generation EU program (Piano Nazionale di Ripresa e Resilienza – Missione 4, Componente 2, Investimento 1.3, D.D. 1551.11-10-2022, PE00000004).

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Notes

1. A *quality characteristic* is defined as a feature of a manufactured item that is critical to its functionality.[19]
2. Variability is considered "natural" when describing a process that operates consistently and without anomalies that can be attributed to machine failures, imperfect materials, or human errors.[19]
3. *Large-volume metrology* is a branch of metrology dealing with the measurement of objects whose dimensions range from few meters up to tens of meters.[32]
4. The exact geometry of the panel is not disclosed for reasons of corporate confidentiality.

5. For each geometrical distance, verification is carried out according to three steps: (i) three-time repeated measurement of the spatial coordinates (x, y, z) of the first endpoint and determination of the average position; (ii) three-time repeated measurement of the spatial coordinates of the other endpoint and determination of the average position; (iii) calculation of the Euclidean distance between the previous average positions. The standard uncertainty $u \approx 0.45$ mm is assumed to include the main contributions of uncertainty involved in determining the final distance result (e.g. instrument resolution and calibration, environmental conditions, positioning of the contact probe, relative distance and angle between the total station and the contact probe, etc.).[4]
6. That is, $\frac{USL-LSL}{u} \geqslant 4$, as specified in ISO 14253-1:2017,[20] Appendix A.
7. It is worth mentioning that such risks can never completely be eliminated. Outside the guard bands, however, these risks can be regarded as reasonably negligible because they are $\leqslant 5\%$. Hence the use of the adjective "undoubted"– which from a purely theoretical viewpoint would be improper – referring to the zones marked with the symbols "✓" and "×."
8. Each panel is characterized by different construction elements of varying complexity, whose conformity should be verified after the manufacturing operations. The reference *population* consists of the (various) constructive *elements* on the panels, made by (various) operations. For each panel, quality engineers have identified a *sample* of constructive (geometric) elements whose conformity should be verified: some *quality characteristics* of interest (i.e. reference distances in the exemplified case study). Since production is extremely flexible, the number and type of quality characteristics (elements) may vary from panel to panel (or sample to sample). During conformity verification, the quality characteristics that meet the relevant specifications are classified as *conforming*, the others as *nonconforming*. It is therefore possible to associate each specific panel with a corresponding defectiveness, as illustrated below.
9. Since $p \approx \bar{p} = 14.2\%$, in this specific case the condition $n_i \cdot p \geqslant 5$ is actually satisfied when $n_i \geqslant 36$.

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Appendix

Consider the following additional figures, which supplement what is reported in Section 3.1.

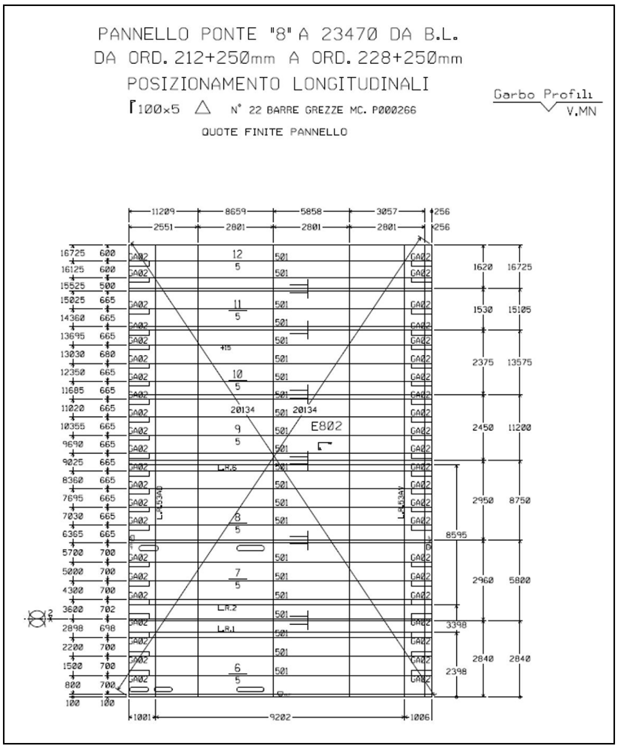
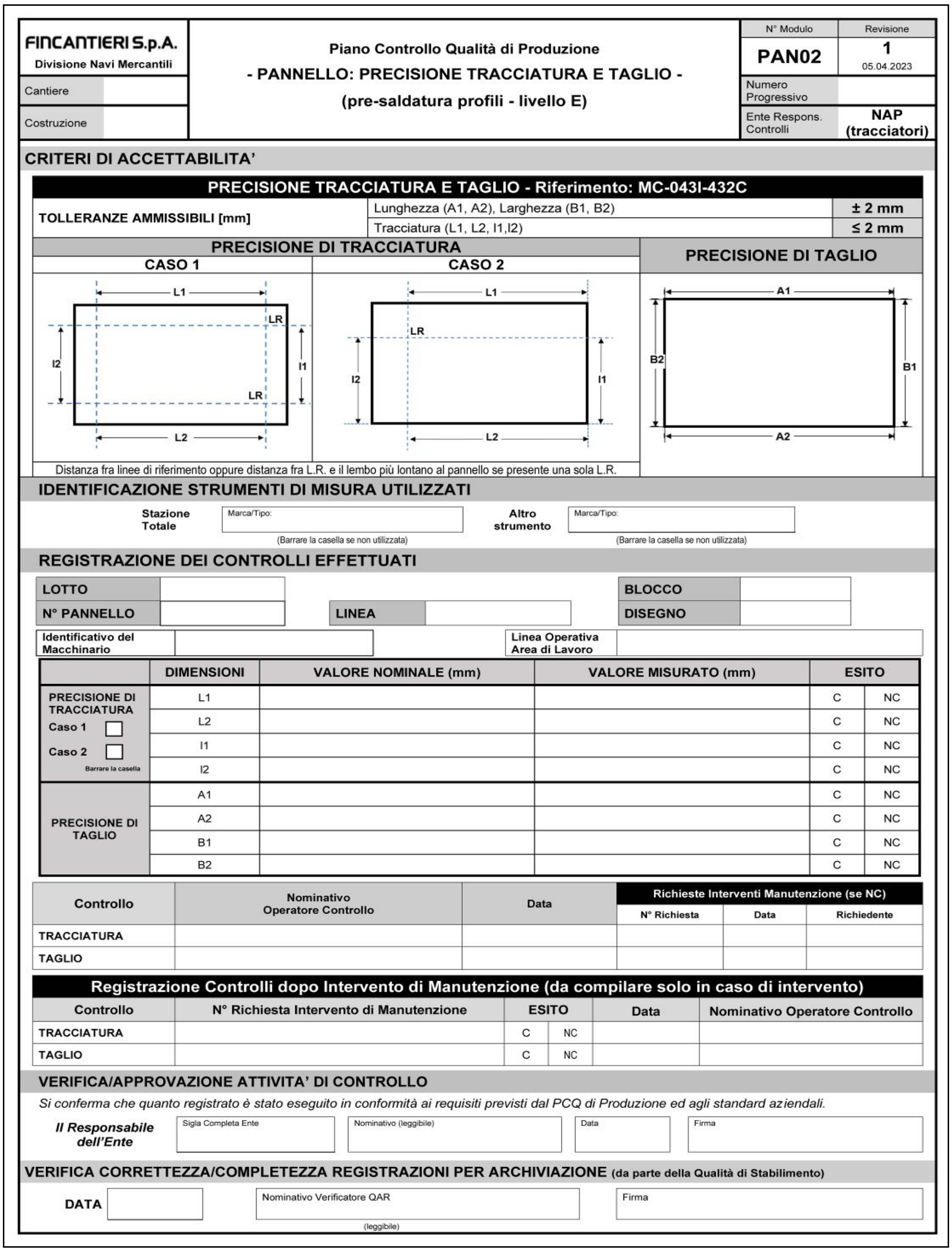


Figure A1. Example of a technical drawing related to a specific panel at a Fincantieri S.p.A. shipyard, showing the nominal values of some quality characteristics related to the positioning of longitudinal stiffeners. For reasons of industrial confidentiality, data are partially omitted/distorted.



FINCANTIERI S.p.A. Divisione Navi Mercantili	Piano Controllo Qualità di Produzione - PANNELLO: PRECISIONE TRACCIATURA E TAGLIO - (pre-saldatura profili - livello E)	N° Modulo	Revisione
Cantiere		PAN02	1 05.04.2023
Costruzione		Numero Progressivo	
		Ente Respons. Controlli	NAP (tracciatori)

CRITERI DI ACCETTABILITA'

PRECISIONE TRACCIATURA E TAGLIO - Riferimento: MC-043I-432C

TOLLERANZE AMMISSIBILI [mm]		
	Lunghezza (A1, A2), Larghezza (B1, B2)	± 2 mm
	Tracciatura (L1, L2, I1,I2)	≤ 2 mm

PRECISIONE DI TRACCIATURA — **CASO 1** — **CASO 2** — **PRECISIONE DI TAGLIO**

Distanza fra linee di riferimento oppure distanza fra L.R. e il lembo più lontano al pannello se presente una sola L.R.

IDENTIFICAZIONE STRUMENTI DI MISURA UTILIZZATI

Stazione Totale	Marca/Tipo: (Barrare la casella se non utilizzata)	Altro strumento	Marca/Tipo: (Barrare la casella se non utilizzata)

REGISTRAZIONE DEI CONTROLLI EFFETTUATI

LOTTO				BLOCCO	
N° PANNELLO		LINEA		DISEGNO	
Identificativo del Macchinario				Linea Operativa Area di Lavoro	

	DIMENSIONI	VALORE NOMINALE (mm)	VALORE MISURATO (mm)	ESITO	
PRECISIONE DI TRACCIATURA Caso 1 ☐ Caso 2 ☐ Barrare la casella	L1			C	NC
	L2			C	NC
	I1			C	NC
	I2			C	NC
PRECISIONE DI TAGLIO	A1			C	NC
	A2			C	NC
	B1			C	NC
	B2			C	NC

Controllo	Nominativo Operatore Controllo	Data	Richieste Interventi Manutenzione (se NC)		
			N° Richiesta	Data	Richiedente
TRACCIATURA					
TAGLIO					

Registrazione Controlli dopo Intervento di Manutenzione (da compilare solo in caso di intervento)

Controllo	N° Richiesta Intervento di Manutenzione	ESITO		Data	Nominativo Operatore Controllo
TRACCIATURA		C	NC		
TAGLIO		C	NC		

VERIFICA/APPROVAZIONE ATTIVITA' DI CONTROLLO

Si conferma che quanto registrato è stato eseguito in conformità ai requisiti previsti dal PCQ di Produzione ed agli standard aziendali.

Il Responsabile dell'Ente	Sigla Completa Ente	Nominativo (leggibile)	Data	Firma

VERIFICA CORRETTEZZA/COMPLETEZZA REGISTRAZIONI PER ARCHIVIAZIONE (da parte della Qualità di Stabilimento)

DATA		Nominativo Verificatore QAR (leggibile)	Firma

Figure A2. Example of a form used to report the results of dimensional inspections of quality characteristics of interest at a Fincantieri S.p.A. shipyard; for reasons of industrial confidentiality, the form is intentionally left incomplete.