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Enhancing sustainability in the production of cruise-ship modules through quality monitoring

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Abstract

Constructing cruise-ship hull is long, complex and requires relatively precise metal carpentry, welding and assembly operations. Timely detection and correction of anomalies is vital to the sustainability of the process, in terms of reducing production time and costs. This paper presents a novel *statistical quality control* (SQC) methodology for monitoring the workshop for the production of so-called "modules" within shipyards, i.e., roughly parallelepiped sub-assemblies of large dimensions (on the order of several tens of meters on each side), obtained through manual carpentry and welding operations. 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 modules, 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 Leica RTC360 laser scanner), following the ISO 14253-1:2017 standard. A real-world case study at an Italian Fincantieri S.p.A. shipyard demonstrates its practical application.

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Keywords: Shipbuilding; Sustainable production; Large-volume metrology; Laser scanner; Control chart.

1. Introduction

The production of cruise ships is an extremely long and complex process. To cope with increasingly fierce competition, especially from Eastern countries, and the rising costs of raw materials and labour, over the last 10-15 years several Western shipyards – including those of the Italian Fincantieri S.p.A. – have shifted their focus to the production of small-medium and extra-luxury cruise ships, with higher levels of customisation and quality, which allow for higher profit margins [1]. This strategic orientation, which is in line with the dictates of the so-called "Made in Italy" production [2], requires particular commitment and flexibility, starting from the design of the cruise ship, the supply-chain management, up to production processes and quality of the final product.

The focus of this paper is on the hull construction process of cruise ships, which 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 with vertical structures 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 [3]. This process is challenging due to several factors [4]:

- The large size and the relatively high level of customization of the parts manufactured.
- The unpredictable sequence of operations, due to the availability of large teams of operators, equipment and *rework* that becomes systematically necessary.
- The inevitable presence of deviations from the nominal design dimensions, which can lead to nonconformities.

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Dimensional specifications related to the geometry of parts manufactured in cruise-ship shipyards are usually around a few millimeters from nominal (design) values [5, 6]. 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 [3].

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 also to provide guidance to operators [7]. 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* during the dimensional verification of the quality characteristics of interest.

This paper proposes a new SQC methodology for monitoring the module-production workshop within cruise-ship shipyards, which is relatively "slow", since work-in-progress parts can stand for about 3-4 weeks before moving to the final assembly stage. The proposed methodology is based on a standardized *p*-chart that considers the measurement uncertainty in conformity verification, in line with the ISO 14253-1:2017 standard, and accommodates the fact that modules are highly customized [8]. Conformity verifications are performed through a state-of-the-art instrument for *large-volume metrology* (LVM), namely a Leica RTC360 3D laser scanner [9-11].

The reminder of this article 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 – and provides a preliminary sustainability analysis. The third section provides concluding remarks on the practical implications of this research, highlighting its potential, limitations, and future research insights.

2. Preliminary information

2.1. Case study

The manufacture of cruise-ship *modules* includes almost exclusively manual work operations that can be subdivided into three types, in chronological sequence [3, 4]:

1. Metal carpentry;
2. Welding and joining;
3. Finishing on critical surfaces.

The work operations relating to each of the three types are typically assigned to a single team of specialised operators (internal or external to the company), who work on the module being processed for approximately 7-10 working days. At the end, the next type of operation is conducted by a subsequent team of specialized operators, which replaces the previous one. The conformity of the work carried out by a certain team can be gradually verified by monitoring specific (geometric) quality characteristics on the module in progress.

Let us consider a specific module-production workshop in a Fincantieri S.p.A. shipyard, in which it is assumed that metal carpentry is the most critical type of operation in terms of generating possible non-conformities. Furthermore, it is assumed that the team of carpenters has been renewed and that it is necessary to monitor their work progress. For these reasons, an SQC tool focused exclusively on carpentry operations has to be developed.

Fig. 1 represents the fabrication of the aft module of a cruise ship, by assembling several units. The 3D point cloud is the result of a preliminary scan using a laser scanner, useful for carrying out some dimensional conformity verifications. In this context, quality engineers define several quality characteristics to be monitored during operations, specific to the module being processed. Table 1 provides an example of (geometric) quality characteristics for a specific module, primarily distances between reference positions, with specifications of ±4 mm around their nominal value.

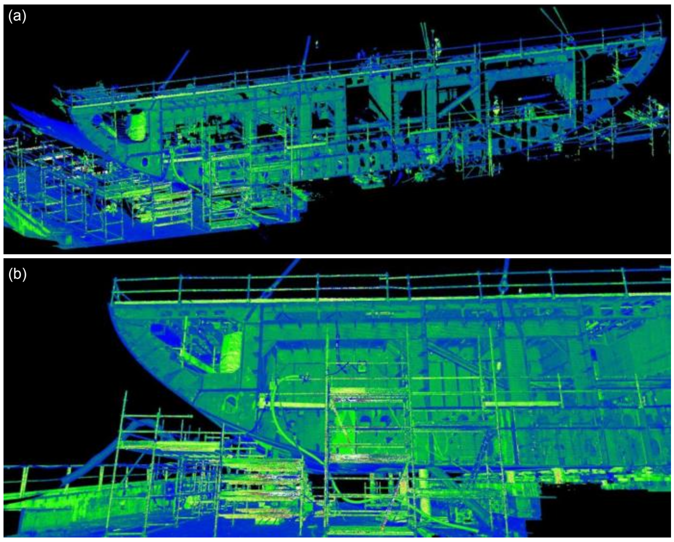

Fig. 1. 3D point cloud obtained through a scan of the aft module of a ship under construction at a Fincantieri S.p.A. shipyard. (a) Perspective view and (b) frontal view.

Table 1. Dimensional verifications for a specific module. Thirty-four quality characteristics (i.e., distances between reference positions on the module surface) are verified using a Leica RTC360 3D laser scanner (with standard uncertainty $u \approx 0.90$ mm for single-distance measurements, cf. Sect 2.2). Conformity verification follows ISO 14253-1:2017, with a guard band of $g \approx 1.48$ mm around each specification limit (see Sect. 2.3 for details). "Δ" indicates deviation from the nominal value. Symbols "✓", "✗", and "?(✓)" represent undoubted conformity, undoubted nonconformity and dubious conformity, respectively (cf. Sect. 2.3).

Qual. charact. no.	Specifications [mm] *NV*	*LSL*	*USL*	*y* [mm]	$\Delta = y - NV$ [mm]	Conforming?
1	15500	15496	15504	15500.2	0.2	✓
2	23270	23266	23274	23274.0	4.0	?(✓)
3	15070	15066	15074	15064.7	-5.3	?(✓)
4	21070	21066	21074	21071.3	1.3	✓
5	20260	20256	20264	20268.7	8.7	✗
⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	18120	18116	18124	18122.1	2.1	✓
33	15910	15906	15914	15908.5	-1.5	✓
34	20710	20706	20714	20716.6	6.6	✗

2.2. 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, laser trackers, and total stations equipped with (contact/non-contact) probes, which enable the rapid acquisition of 3D data for surface reconstruction [9].

For dimensional verifications during module processing, a practical balance between measurement convenience and accuracy can be achieved using state-of-the-art laser scanners, which are compact, lightweight, operate wirelessly, and can capture clouds of tens of millions of points in just a few minutes [10]. In our case study, we used the Leica RTC360 wireless laser scanner (see Fig. 2) [11]. The instrument's performance was assessed, yielding a conservative $u \approx 0.90$ mm standard uncertainty for single-distance measurements.

Fig. 2. Leica RTC360 wireless laser scanner used for conformity verifications at a Fincantieri S.p.A. shipyard.

2.3. 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 [8]. 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). Fig. 3 shows that doubt in conformity or nonconformity classification may arise in the "?" zones around specification limits, requiring the application of a suitable *decision rule*.

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 false conformings (e.g., to prevent potential failures) prevails. Decision rule #1 bilaterally extends the conformity range of specification limits by a guard band of semi-width g (i.e., conformity range equal to zone "✓" plus zone "?", in Fig. 3), while decision rule #2 bilaterally narrows it by the same amount (i.e., conformity range corresponding to zone "✓" only).When standard uncertainty (u) is much smaller than the specification interval (USL – LSL), a $g \approx 1.64 \cdot u$ guard band maintains risks (of false nonconformings and false conformings) below 5% for both rules (see Fig. 3) [8].

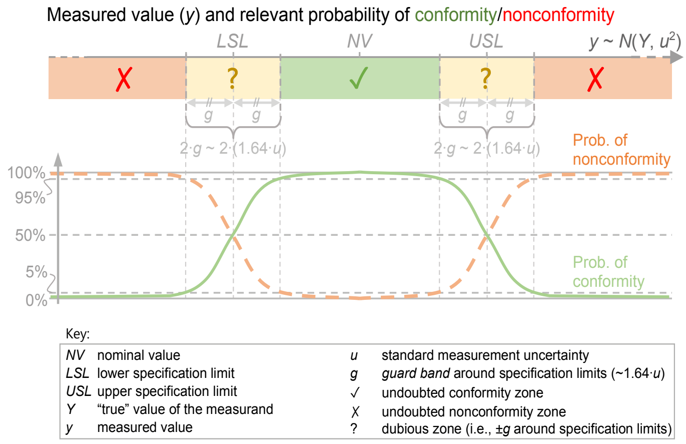

Fig. 3. Conformity verification according to ISO 14253-1:2017, based on the measurement result (y) of a quality characteristic. Decision rule #1 extends the conformity range to zone "✓" plus zone "?", while decision rule #2 narrows it to zone "✓" only. In the case study, decision rule #1 was adopted.

3. SQC methodology

3.1. Control chart selection

Selecting a control chart for monitoring the manufacturing process of modules should consider its unique characteristics: inherent complexity, different types of work operations (cf. Sect. 2.1) relatively slow transition of manufactured parts (i.e., 3-4 weeks), high customization, and diverse conformity verifications (in type and number) from module to module.

It would be appropriate to conduct necessary dimensional verifications gradually, without waiting for the completion of the entire module, to prevent the propagation of errors or potential deviations in terms of work quality. Additionally, it would be appropriate to monitor different types of work operations (such as metal carpentry, welding, surface finishing) separately, since their variability may not be directly comparable.

In light of these considerations, the standardized p control chart for attributes can be used to monitor work operations of a specific type (metal carpentry in this case). Precisely, the overall work activity is divided into individual *operations*; each specific operation represents an i-th sample with a variable number of specific quality characteristics, which are used to verify the degree of conformity with the relevant specification limits [8]. For example, Table 1 exemplifies an i-th sample (operation) with $n_i = 34$ quality characteristics, verified using the Leica RTC360 laser scanner. Consistently with the assumptions introduced in Sect. 2.1, the focus will be exclusively on operations related to metal carpentry, as they are considered the most critical in this case. Each quality characteristic is marked as conforming ("✓") or nonconforming ("✗"). The total number of defectives ($d_i \in [0, n_i]$) and the defectiveness of the i-th operation ($p_i = d_i/n_i \in [0,1]$) can then be calculated.

The verification of different quality characteristics and the determination of an overall operation-by-operation defectiveness (d_i) are justified when the *natural variability* among quality characteristics is relatively homogeneous, specification ranges are similar (e.g., ±4 mm around nominal values), and measurement uncertainty for the different measurements is comparable. These conditions are met in the case study.

3.2. Construction of the standardized p control chart

The construction of the standardized p-chart requires a dataset of at least 15-20 samples (i.e., operations) of no less than 20-25 elements (i.e., quality characteristics) each. In the case study, 20 operations were used, each with different quality characteristics (in number and type). It should be noted that these operations involve three different modules ("A", "B" and "C") and generally take place over a whole day, as shown in the first column of Table 2. The significant measurement uncertainty (i.e., $u \approx 0.90$ mm, cf. Sect. 2) with respect to specification limits 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. 3).

Table 1 (in the last column) exemplifies the outcome of some conformity verifications for the specific sample #1, revealing $d_1 = 3$ nonconforming quality characteristics out of $n_1 = 34$, resulting in a sample defectiveness of $p_1 = 3/34 \approx 8.8\%$. Among the 31 conforming quality characteristics, 16 are undoubtedly conforming ("✓"), and 15 are doubtfully conforming ("?(✓)"). Extending these verifications to the remaining 20 operations generates the data in Table 2. The number of defectives (d_i) in an i-th operation with n_i quality characteristics follows a binomial distribution, with mean μ_d and variance σ_d^2. Based on available data, the best estimate of the defectiveness (p) of the whole metal carpentry work is [7]:

$$\bar{p} = \frac{\sum_{i=1}^{21} d_i}{\sum_{i=1}^{21} n_i} \approx 15.9\%. \tag{1}$$

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

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

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, the condition $n_i \cdot p_i \geq 5$, which is necessary for approximating d_i and p_i as normally distributed variables, is generally met [7, 12].

Fig. 4 presents the standardized p-chart with z_i values from Table 2, along with (three-sigma) control limits ($UCL = 3$, $CL = 0$, and $LCL = -3$) [7]. 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 [7, 12]. Therefore, this ensures that the control chart is constructed with the process under stable conditions – i.e., without "assignable" sources of variability – and that it can be used to monitor the future evolution of the process.

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

Sample # (module.operation, date)	n_i	d_i	p_i	z_i
#1 (A.1, 19-june)	34	3	8.8%	-1.125
#2 (A.2, 20-june)	33	2	6.1%	-1.542
#3 (A.3, 21-june)	26	3	11.5%	-0.605
#4 (A.4, 22-june)	35	6	17.1%	0.206
#5 (A.5, 23-june)	30	8	26.7%	1.618
#6 (A.6, 26-june)	25	6	24.0%	1.112
#7 (A.7, 27-june)	30	8	26.7%	1.618
#8 (B.1, 28-june)	32	6	18.8%	0.446
#9 (B.2, 29-june)	36	5	13.9%	-0.325
#10 (B.3, 30-june)	36	6	16.7%	0.131
#11 (B.4, 3-july)	35	4	11.4%	-0.719
#12 (B.5, 4-july)	36	7	19.4%	0.587
#13 (B.6, 5-july)	40	9	22.5%	1.147
#14 (C.1, 6-july)	30	5	16.7%	0.119
#15 (C.2, 7-july)	36	4	11.1%	-0.782
#16 (C.3, 10-july)	32	3	9.4%	-1.006
#17 (C.4, 11-july)	32	5	15.6%	-0.038
#18 (C.5, 12-july)	26	5	19.2%	0.469
#19 (C.6, 13-july)	27	5	18.5%	0.377
#20 (C.7, 14-july)	38	3	7.9%	-1.346
	$\sum_{i=1}^{m} n_i = 649$	$\sum_{i=1}^{m} d_i = 103$	$\bar{p} = 15.9\%$	

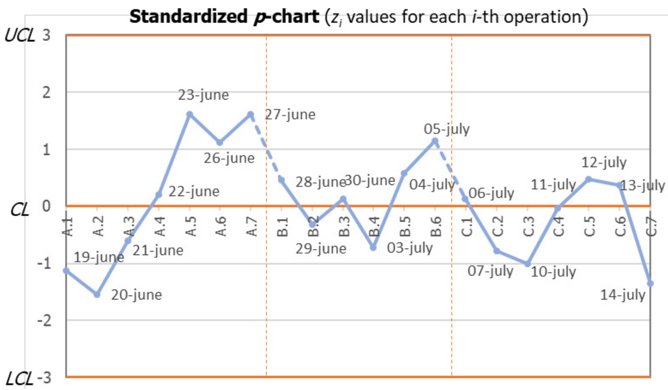

Fig. 4. Standardized p-chart related to the z_i values in Table 2. Operations carried out on the same module ("A", "B", "C", as indicated in the horizontal-axis labels; cf. Table 2) are separated by dotted vertical lines.

3.3. Preliminary sustainability analysis

The concept of sustainability of a manufacturing process is broad and has several practical implications, ranging from the need to reduce the consumption of raw materials, energy, resources and water, to the choice of cost-effective end-of-life strategies, with maximization of recycling/reuse of products and/or components [13]. In the specific field of hull construction in shipbuilding, structured sustainability analyses are notably absent from the scientific literature, likely due to a combination of factors [14]. Firstly, this manufacturing sector is relatively *niche* and has seen little significant technological innovation over the past 4-5 decades [1]. Additionally, confidentiality and industrial secrecy often inhibit the publication and dissemination of specific quantitative data. Moreover, hull construction is a complex, multifaceted, and fragmented manufacturing process, making the execution of in-depth sustainability analyses challenging. For instance, directly measuring energy and material consumption during various stages is far from straightforward. Predicting the extra-cost associated with the final assembly phase, due to inaccuracies in earlier stages, is equally difficult; although there are some simulation models in the literature for approximating this extra-cost, they are highly specific to individual productions and are not easily generalizable [5].

In this study, we conducted a preliminary sustainability analysis, focusing on metal-carpentry operations, as the corresponding imperfections may hinder the successful final assembly of modules. Given the practical impossibility of measuring energy and raw material consumption accurately, this preliminary study was based on an analysis of production costs and times. In particular, drawing on recent experiences at some Italian Fincantieri S.p.A. shipyards, we conducted a brief survey of rework interventions aimed at correcting anomalies found in the final assembly, mostly due to imperfect metal-carpentry operations. This survey revealed that such interventions can increase man-hours by up to 25-30%. Assuming that the expenditure of resources (mainly energy and raw materials) is approximately proportional to the working time, a similar percentage increase can be assumed. As rework should be carried out in the final-assembly phase, in order to avoid delaying the completion of the work, it is often necessary to increase the number of personnel – by using external teams and overtime shifts (e.g. night and/or weekends) – resulting in cost increases of sometimes more than 50%.

Hence the great potential of SQC tools aimed at reducing or at least detecting anomalies at an early stage, including the proposed control chart. This tool facilitates timely rework in the right production phase, where repair times and costs are significantly lower than in the final-assembly phase. In the future, we aim to more precisely estimate the specific benefits associated with implementing the proposed control chart in a specific Fincantieri S.p.A. shipyard.

4. Conclusions and outlook

This paper proposed an operational methodology, which is useful for overseeing the shipyard manufacturing operations on modules, 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 rework in final assembly. An innovative aspect is handling the measurement uncertainty through following 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 later stages; for instance, measurements could be reinforced around the area of concern and/or more precise instruments might be employed. The proposed approach provides flexibility, allowing quality managers to choose the most suitable decision rule. This is also in line with ISO/TR 14253-6:2012(E), which contemplates intermediate decision rules of *relaxed acceptance* and *relaxed rejection*, with which more conservative measures can be associated [15].

Although in the case study at a Fincantieri S.p.A. shipyard, a Leica RTC360 3D wireless laser scanner 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, which require investigation. Any out-of-control situation detected by the control chart prompts investigations into root causes. For instance, increased 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 [7]. 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 [7, 12].

The attention to monitoring the quality of the production process is fundamental for its sustainability, in terms of reducing times and costs for rework, as also pointed out by the previous preliminary sustainability analysis.

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 [7, 12]. Defining the specific quality characteristics for each operation is delicate, as they should constitute an adequate amount of features that are representative of the process quality, without redundancy; expertise from quality engineers is crucial. Additionally, all conformity verifications for a specific operation 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.

Regarding the future, it is planned to develop similar *ad hoc* SQC methodologies for other shipyard workshops with different characteristics.

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