Process Capability Factors in the Production of Curved Panels

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The inaccurate production of curved block sections leads to high adjustment- and reworking expenditures in the assembly process. With instruments of Statistical Process Control (SPC) it will be possible to identify the source of inaccuracy and investigate the efficiency of technical steps to improve the precision in production. Therefore, the current state of the art in curved block assembly and schemes for static analysis has been evaluated.

KEY WORDS

Shipbuilding, Curved block sections, Accuracy-control, Statistical process control, Process capability indices, Six Sigma Methodology,

INTRODUCTION

Precise-manufacturing represents one of the key research subjects within the department of manufacturing-engineering. Solutions for the introduction of a tolerance system, that considers welding shrinkage for the parallel central-nave, have already been put into practice successfully, *Heinemann et. al (1999)*. As a result, in different levels of shipbuilding-manufacturing the implementations of the recommended measures have led to a reduction in adjustment- and reworking-expenditures of approx. 20%, *Heinemann (1997)*.

But this manufacturing advantage cannot be applied to sections with biaxially-curved contact surfaces, which together account for approx. 15-20% of the entire ship-hull weight [Fig. 1].

Due to the demand for fast and energy-efficient vessels with a high load capacity, the ship-hull-shape will change in such a way as that the amount of sections with curved contact surfaces will rise above the abovementioned percentage.

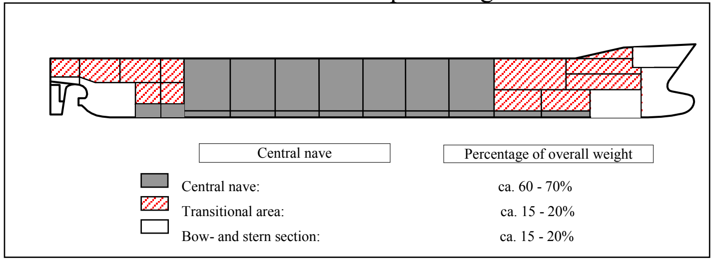


Fig. 1: Typical ratios of semi manufactured product of a container vessel, based on the ship hull mass, *Lerche et. al (1998)*

As a consequence of the completed research work on precise construction of Curved Panels, *Wanner et. al (2004)*, it has to be stated that a precise production is not, or only to a limited extent, possible. The detected dimensional deviations vary considerably and because of systematic measurement deviations a measurement-compensation is still impossible.

To stabilize the manufacturing process it is necessary to establish an uninterrupted monitoring of the manufacturing quality. A SPC (statistic process control) is perfectly appropriate for that purpose.

To meet this demand, a system of production-process-accompanying measurements and statistical analysis has been developed, which will be described below.

STATE OF THE ART IN THE PRODUCTION OF CURVED PANELS

Manufacturing Technology

The manufacturing of Curved Panels takes place in several production levels, from single components (plates, profiles) and intermediate products (carrier, panels) to the finished product (curved section).

A "universal intermediate product arrangement" for the manufacturing of biaxial-curved surface and volume assemblies was developed by *Zorn et. al (2000)*. It divides the production order into production levels and production alternatives.

Dimensional- and size-accuracy of the components are the basis for the accuracy of the assembly process and the section respectively. "Layout" and "shaping" are the Controlling and forming manufacturing processes.

Plates

The **cutting** of the outer shell plate is performed, according to the nesting-pattern, through thermal cutting (plasma-cutting, suitable for thermal cutting). Defined stop marks on the burner table ensure a correct board positioning. The plates are fixed by their own weight. The NC-oxygen-cutting machine is programmed via the nesting cad-data. The program starts after approaching a base-point. Before the programme is executed, the board-position is again partially checked. The program process consists of 2 steps:

1. application of indications and marks
2. layout of the plate according to target data

The marks aim to depict the following information:

- framing outline
- moulded line of the frame

- bending line in longitudinal direction (LBU)
- dividing line deformation area/ area that needs no deformation
- direction of rolling

The plate-layout accuracy is depended upon the positioning accuracy of the oxygen cutting machine. For plasma cutting (e.g. oxygen cutting machine OMNIMAT) and for autogen thermal cutting (e.g. oxygen cutting machine NUMOREX) these accuracies are given with ± 1mm. Since the marking machine is closely linked to the axis of the combustion aggregate, the above mentioned accuracies are to be expected. (Marker-line weight: 1-1,5mm)

The deformation is carried out on the press (e.g. roll bending press), whereas different tools (bending roll, pin roll) are needed for the production of the possible types of biaxial-curved plates, such as twisted plates, biaxial unidirectional-curved plates and saddle plates. Moulding tools or models are used as shape test equipment. When variable moulds are applied the bending line of the respective profile is highlighted on the plate.

At present, the deformation quality is directly linked to the experience of the transformer because he assesses bending lines in frame direction, with the help of applied moulding tools, as well as the longitudinal bay which is measured with the help of the mould-base.

Profiles

The cutting of the profiles is carried out on the NC oxygen cutting machine. Separating the back cuts, breakthroughs and trimming all proceed according to the program. In profile cutting manufacturing tolerances of ±0,5mm (profile cutting robot) are achieved, comprising trimming with seam preparation.

The **deformation** can be carried out on the profile bending machine (depending on the transformer's experience) and/ or according to the programme (fixed values are set for in-feed and lift), e.g. all-purpose bending machine UFB4000 of IMG Rostock. The manually operated testing of the produced bending lines is conducted via bearing or via setting a chalk line onto the inverse line, which is manually applied on the building site, according to allowances charts or highlighted automatically. Bent profiles are tested with models. The deformation with an automatically operated profile bending machine e.g. profile bending machine UFB4000 is conducted in a very precise manner in regard to the preset tolerances, *IMG (2005).*

Building devices

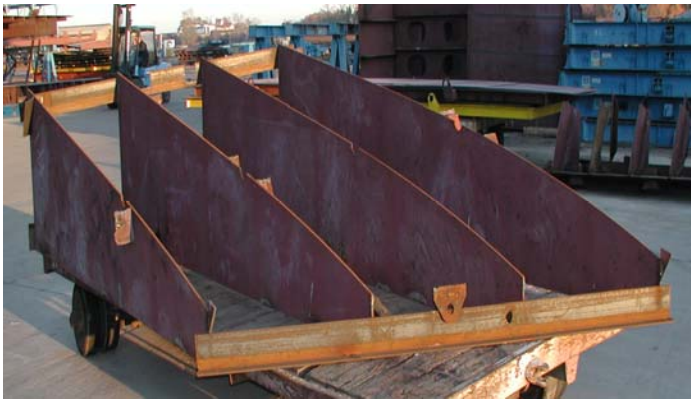
The following construction methods are common in German shipyards.

- „overhead" – construction method [Fig. 2]
- Usage of jig [Fig. 3]
- Usage of variable jig pillars [Fig. 4]

In the **overhead construction method** the deck is designed and taken as a basis for the assembly of cross and horizontal bracing. After the welding of the interior structure and after inserting the outer shell profiles into the frame carriers, the outer shell plates are usually applied and welded.

The advantage of this construction method is that only one even construction restraint is needed. Cross and horizontal bracings are positioned with common measurement equipment, such as lead and angle. This simple procedure is especially advantageous in case of constructing over multiple decks. However, it is possible to semi-automatically weld together the single outer shell plates in forced position and connect it with the interior structure [Fig. 2]. In this case submerged welding is inapplicable for the welding of butt seams.

Fig. 2 Overhead manufacturing method for curved block sections



Jigs [Fig. 3] are applied in the manufacturing of inflexible panels which only provide little scope for adjusting to the next section.

Fig. 3 Outline - jig for bended ship structures

The outer shell plate is then constructed and partly tacked with cleats onto the jig pillar near the plate border. Next, the profiles are applied and welded. This procedural method minimizes deformation as a result of welding distortion but also causes relatively high self-equilibrating stress within the completed section.

Variable jig pillars [Fig. 4].offer the possibility to pattern the outer shell-geometry with particular sampling points.

Fig. 4 Jig - pillar with applied and clamped ship hull plates

Jig pillars consist of jigs mounted on cylinders and socket that are arranged in a certain grid pattern. These jigs, which are flexible during the insertion, consist of pipes and a jig head. They can be adjusted steplessly. The positioning can take place steplessly (through a clamp ring), stepped (through holes and gudgeons) or combined (pre-adjustment through holes, precise adjustment through steplessly variable jig head). The main advantage over jigs is that jig pillars are flexibly adjustable. The arrangement of the plate plan can be chosen in a manner that allows submerged welding. After profiled ere being applied to the plate, plan weld seams in horizontal position are possible.

Quality management in shipbuilding production

The quality requirements in the manufacturing of certain parts are basically related to the quality of the edge preparation and to the compliance with acceptable gaps. The classification and building regulations of the "Germanischer Lloyd" have to be regarded as a standard, *GL (1999).* It refers to the compliance with seam-form and pitch as indicated in shipyard specific construction documents.

In the process the tolerances are valid for length and width along the curve direction [Tab. 1]. The tolerance indications given in *IACS (1999)* provide average instructions for authoritative measurements. These are regarded as standard. Additionally, a maximum limit for the deviations is given. The tolerance checklist according to *IACS (1999)* is based on the diverse experiences of international classification societies. Therefore, two indications are given (standard and limit) to be able to consider the full spectrum of experience.

Especially in edge preparation, during the cutting process, the machine accuracy allows to include a certain permissible air gap.

In positioning the single to form a plate, the welding gap compliance guidelines for full seam butt welding are valid.

Fig. 5 shows an extract from *DIN (2004)*, that indicates the acceptable air gap width in relation to the work-piece thickness and the seam preparation technique.

Tab.1 Tolerances for bended plates and components, *IACS (1999)*

	Standard	Limit
Curved Plate Length & width	± 2,5mm	± 5mm
Spatial Curved Elements Length & width	± 2,5mm	± 5mm

Currently, there are no specifications in shipbuilding standards which regulate the form-tolerances for curved sections. The quality requirements for the deformation of components can be referred to the air gap between the deformed profile and the deformed plate. In this case the guidelines for fillets are valid. Especially for fillets *DIN (2003)* defines an excessive or insufficient pitch as irregular. After the processes are being sorted into evaluation-groups, the limit values for certain assembly processes can be found in the following table. [Tab. 2].

According to this standard *DIN (2003)* the fillets on curved panels and panels are generally manufactured according to evaluation-group C, whereas a is the designed weldseam thickness and b the designed weldseam width. The classification of the evaluation-groups in *DIN (2003)* is set in *VSM (1995)* for shipbuilding assemblies. Consequently, an acceptable air gap of maximal 3 mm is produced. The compliance with this requirement in profile deformation is possible because of straightness control of the inverse lines and because of the application of moulding tools respectively through visual inspection. During the checking of the deformed plate an air gap of this dimension is assessable by applying models or through adjustable moulds.

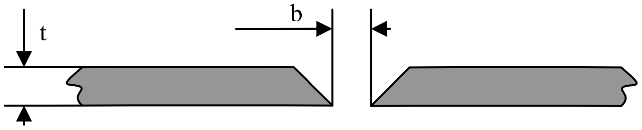
In Japanese shipbuilding the tolerance guidelines for the manufacturing of curved panels are considerably more comprehensive. In addition to functional tolerances, manufacturing tolerances are defined, which enable the testing for correct curvature during production, *NAJ (1991).* The tolerance guidelines for the welding gap are given for the single components with 5 mm and with 8 mm for the butt joint.

Tab. 2 Limits of inordinateness for a welded joint, DIN (2003)

Limits for the inaccuracies of evaluation groups		
low	medium	high
D	C	B
b≤1mm+0,3a	b≤0,5mm+0,2a	b≤0,5mm+0,1a
Max. 4mm	Max. 3mm	Max. 2mm

a - designed seam thickness [mm]

b- designed seam width [mm]



Butt weld, unilaterally welded		
Workpiece thickness t	Denotation	Gap b
$t \leq 4$	I- seam	b ca. t
$3 \leq t \leq 8$ $3 \leq t \leq 10$	V- seam	$6 \leq b \leq 8$ $b \leq 4$
$t \geq 16$	Steep flanks- seam	$5 \leq b \leq 15$
$5 \leq t \leq 40$	Y- seam	$1 \leq b \leq 8$

Butt weld, bilaterally welded		
Workpiece thickness t	Denotation	Gap b
$t \leq 8$	I- seam	$b \leq t/2$
$3 \leq t \leq 10$	V- seam With backing run	$b \leq 3$
$t \geq 10$	Y- seam with root run and backing run	$1 \leq b \leq 3$
$t \geq 10$	Double Y- seam	$1 \leq b \leq 4$

Fig. 5: Allowed gaps for seam butts, DIN (2004)

ANALYSIS OF THE QUALITY CONTROL IN THE PRODUCTION OF CURVED PANELS

Production standards and tolerance checklists in shipbuilding

General Facts about Manufacturing Standards in Shipbuilding

A comprehensive ISO tolerance and fitting system is valid in mechanical engineering. The procedure of tolerance specification proved valuable in the application of machined manufacturing processes.

In shipbuilding other factors affect accuracy (the main procedure however is welding). In addition to the deviations it variances appear in form and position, caused by welding deformations. Consequently there are functional correlations between the actually independent variances. These have to be defined over a generally accepted toleration principle on the basis of a permanently applicable absolute reference system.

The currently existing industry-specific tolerance guidelines in shipbuilding are not comparable to the ISO tolerance and fitting system. However, there are attempts to create an extensive tolerance system for the production of shipbuilding structures. Such a system deals with ship production as an integral process. An example for this would be the tolerance checklist of manufacturing tolerances, which was developed for the Warnowwerft shipyard. This checklist contains manufacturing tolerances, even for curved sections, which have been detected on the basis of production-related measurements (bilge strake sections). These manufacturing tolerances have been detected during different stages of the ship assembly process. But this checklist does not contain manufacturing tolerances for curved panel sections.

In conclusion, we have to note that manufacturing tolerances in shipbuilding cannot be put on a level with the tolerating system in general mechanical engineering. In mechanical engineering a tolerance is defined as the range in which geometric deviations may occur without affecting the functionality of the assembly. In this process one distinguishes between rejections and rework. But, also rejected parts can be reworked if it is considered technologically meaningful. E.g. a shaft with a diameter which is too small (rejection) can be reworked with a shrunk-on ring.

In shipbuilding manufacturing the functionality of the intermediate product (section) in case of noncompliance with the tolerances is achieved through additional rework which enables the adjustment of the section's form so that the functionality is guaranteed.

According to *Nikolay (2002)* the tolerance instructions applied in shipbuilding can be divided into two categories:

Category 1	Tolerance instructions which only include important functional tolerances for the end product (ship).
Category 2	Tolerance instructions which regulate functional and manufacturing tolerances for single components, assemblies and sections.

Based on this classification and with regard to its importance for the production of curved panels the tolerance instructions are depicted in the next table.

ISO tolerance instructions which exceed those depicted in tab. 3 are internationally regulated in a basic size range of up to 3150 mm ("medial lengths"); *DIN (1990, I+II)*,. Due to different and partly controversial methods rules for the basic size range from 3150 mm to 10000 mm (see *DIN (1990,II)*) do only exist nationally as described in *Nikolay (2002)*. For reasons of different international rules the validity of production standards and of general tolerances is part of a ship's building contract. At the same time the production standard as a general rule is given by the construction- controlling classification society. In the majority of the examined shipyards this has been the VSM production standard, external part *VSM (1995)*. Additionally *DIN (1991)* is regarded as a valid standard for single components without tolerance indication.

Tab. 3: tolerance instructions in German shipbuilding

	tolerance instructions in shipbuilding	importance for the production of curved panels
category 1 tolerance instructions which only include important functional tolerances for the end product (ship).	VSM – standard, external part; *VSM (1995)*	specifications about welding gap and offset of the edges
	general tolerance for metal ships; measurement, form and position tolerance for ship hulls, superstructure parts and deckhouses; *BWB (1986)*	tolerance instruction for military purposes, no validity for civil purposes
	general tolerance for metal ships; measurement, form and position tolerance for rudders and ice floes; *BWB (1991)*	
	Shipbuilding and Repair Quality Standard; *IACS (1999)*	specifications about welding gap and offset of the edges
category 2 tolerance instructions which regulate functional and manufacturing tolerances for single components, assemblies and sections.	VSM – production standard in German shipbuilding, internal part; *VSM (1989)*	specification of a tolerance range sphere for the connecting points with the sections. (experience tolerance for the communication of shipyards among each other)
	general tolerance for metal ships; measurement, form and position tolerances for ship hull assemblies, superstructural parts and deckhouses; *BWB (1987)*	tolerance instructionns for military purposes, no validity for civil purposes
	general tolerance for metal ships, measurement, form and position tolerances for ship hull sections, superstructure parts and deckhouses; *BWB (1989)*	
	Japanese Shipbuilding Quality Standard; *NAJ (1991)*	width of the section; length of the section

Classification of the tolerance checklists into the manufacturing standards

Production standards basically provide consistent evaluation criteria for shipbuilding components. Production standards give tolerance instructions which allow tolerances for geometric assembly features. These specifications can be divided into functional tolerances and manufacturing tolerances.

Every single stage of production is assigned to tolerance zones. But a complete inspection of the shipbuilding production cannot be expected. The tolerance instructions of the first category shall form an accepted quality standard that guarantees the steadiness and the industrial safety of the ship and that is acceptable for customers and classification societies *DIN ISO (1991)*. Specifications about the quality level cannot be derived. Yet it is obvious that the tolerances of steadiness-relevant welding connections (welding gap offset of the edges) can only be complied with enormous adjustment efforts or with methods of precise production *Nikolay (2002).* Hence, the guidelines are the target variables of the function “assemble-ability”, with regard to the welding method and of the constructive design of the assembled sections. But that means that in long run a system of standardised, basic size oriented tolerances is impossible in shipbuilding.

The standards of the second category are advancement insofar as they contain additional information on accepted geometric deviations for shipbuilding single components, assemblies and sections (so production tolerances).

In the framework of this paper the following production standards will be inspected closely.

- IACS „No. 47 Shipbuilding and Repair Quality Standard “–(Stand 08/1999); *ICAS (1999)*
- VSM “manufacturing standard of German shipbuilding“ [external & internal part]; *VSM (1989)+(1995)*
- “Checklist manufacturing tolerances – precise production II. stage“
- Japanese Shipbuilding Quality Standard; *NAJ (1991)*

Evaluation of the tolerance checklists

The **IACS- checklist**; *IACS (1999)* is a true quality standard. All processes that concern ship hull production are inspected. But it does not mention the production of biaxial or multi-axial deformed limit surfaces.

Tolerance specifications for curved panels are given (functional tolerances). But these mostly correspond to those of even panels. Slight amendments are only made concerning form- and position tolerances (twisting, rotation, squareness). There are no production tolerances given for this area of production.

The checklist is an up to date quality and production standard for the production of even assemblies. Given that it only contains functional tolerances, namely a production standard of the first category (see tab), it is only applicable to the final examination (through classification society or customer).This checklist does not contain any specifications about measurement tolerances in curved panel production.

The **VSM- manufacturing standard** is separated into an external *VSM (1995)* and an internal part *VSM (1989)*. The external part contains, as well as the IACS-checklist, functional tolerances which serve the inspection of the final product. On the basis of these standards shipyards are able to communicate with classification societies and customers. But just like the IACS- checklist it does not contain any specification about measurement tolerances of curved panels.

The internal part of this production standard was created to enable the shipyards to define geometric tolerances which can be exercised for self- or external produced assemblies. It defines production tolerances which are of importance for the production of curved panels. For instance connecting points of sections a tolerance range sphere is given with a diameter of 16 mm. unfortunately the effect of this component of the standard is enormously limited in production because under the circumstances of adjustment-assembly there is hardly a need for compliance with accuracy in pre-production which includes curved panel production.

This applies also to *Wiebeck (1991)*, which is basically oriented to biaxial curved limit surfaces. It cannot be regarded as an official standard but as an addition to the VSM production standard.

The approach is a holistic inspection of the production process of ship hulls. Product-determined functional tolerances (VSM), technologically determined functional tolerances (e.g. welding standards), product tolerances and valid test tolerances together form a tolerance system.

This checklist *Wiebeck (1991)* is highly qualified to fill the voids of the VSM standard in regard to production tolerances of curved structures in shipbuilding. Since it was especially developed for the application in shipyards it was not published and therefore it is impossible to access advancements of tolerance guidelines for curved panel production. This is unsatisfactory because important preparatory work was done to create a tolerance system that regards the production chain of the product ship as a whole.

The **Japanese Shipbuilding Quality Standard;** *NAJ (1991)* as well as the VSM production standard represents functional and production tolerances. In contrast to the VSM standard this one does not distinguish between an internal and an external part. Consequently the adhered tolerances are presented to the approving classification society and to the customer, too. Contrary to the VSM standard there is no tolerance range sphere given for the toleration of curved panels. It provides tolerances for the geometric dimensions of a section's length and width whereas a clear position of the dimensions to the global coordinate system "vessel" is not defined. This checklist may serve as a standard of comparison for the determination of tolerances in curved panel production. Therefore specifications for length and width of a curved panel are given (T= ±8 mm) additionally form deviations are considered (T= ±20 mm). It is not evident however, how these specifications correspond with the compliance with welding gaps. Given that this tolerance checklist is defined on the basis of mathematical models it can be assumed that a mathematical model is also valid for the relation between welding gap toleration and production tolerances for curved panels.

Measures for the Compliances with Quality Requirement and their Economic Significance

One aim of curved panel production should theoretically be to comply with the functional tolerances of the welding gap dimensions; *IACS (1999), VSM (1995)*. These functional tolerances should guarantee the assemble-ability of the single sections of a steel-ship hull. According to the current state of knowledge of quality in curved panel production, the compliance with functional tolerances is possible only to a limited extent, whereas the deviations do significantly differ from shipyard to shipyard.

To achieve the aim of assemble-ability of the section to ship hull nevertheless, adjustments and subsequent operations will always be necessary. The section is made suitable through assembly forces and the subsequent flame cleaning of allowances (see Fig.6). Between given functional tolerances and expected variations in the assembly of curved panels there is a discrepancy which can only be solved by subsequent work.

Fig. 6 Adjust works and subsequent works at a section butt

The efforts for adjust and subsequent works can be determined partially to the production process of these sections from dimensional deviations of functional tolerances which have to be seen as reason for these works. These rates are represented in fig. 7.

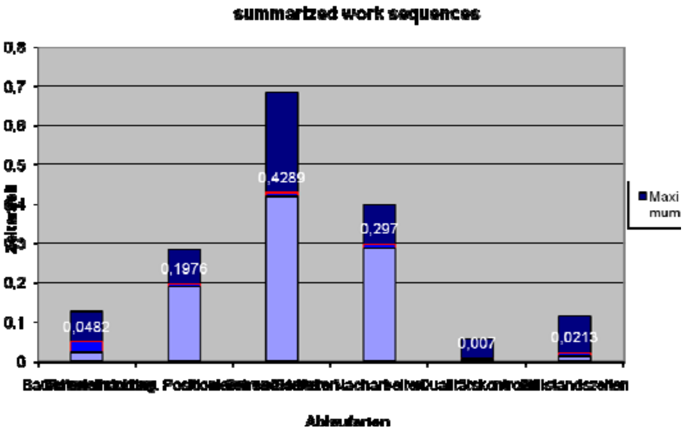


Fig. 7: average time slice of adjust and subsequent work in the process of curved panel production

Deficiencies in development

All examined rules and standards disclose a disproportion between constantly increasing quality requirements on the one hand and ability of establishing a production processes on the other hand. An extensive and generally accepted quality standard is missing. The existing manufacturing tolerances predominantly correspond to production variances which are usually observed (as well as great measurement inaccuracies) while the tolerances of strength, relevant welding joints (offset of the edges, welding gap) can only be complied with enormous adjustment efforts. A continuous toleration of the ship hull, regarding measurement, form- and position deviations, does not exist. The existing tolerance regulations stay limited in their effects because of the general tendency towards using an adjustment assembly, so there is no need for a precise production. The special significance of the compliance with the tolerances in preproduction as a cost cutting measure is insufficiently examined. But this is one of the key elements in securing the future of shipyard industry. Therefore, the creation of an extensive quality system similar to that of the automotive and aviation industry has to be advanced and pushed.

A tolerance checklist that regards ship hull production holistically does not exist yet. The existing tolerance checklists, as part of production standards can be the basis of an extensive tolerance system.

The integration of production tolerances and of the test tolerances is substantial to holistically depict the tolerance system vessel. Therefore, in the future, experience-based tolerances have to be transferred into experimental and theoretical tolerances respectively. These then have to be transferred into a tolerance system based on the ISO system. This provides the basis for the realisation of an extensive quality control system.

Currently three production procedures are applied in curved panel production; the production in a construction device which has to be distinguished in jig pillars and jigs, and the overhead construction method. According to the current state of the art all three production methods hardly show the capability of guaranteeing basic quality-conditions.

That is the reason why shipyards subjectively consider the overhead construction method as more practicable. This is precisely why the problems of compliance with the basic quality-conditions can be avoided easily there. Due to the problematic assembly of the outer shell to the section, in this production method automation for this production method is only possible to a minor degree. So there is no possibility to achieve the stabilization of production through automation. In the following this paper will show that the problems of compliance with qualitative basic conditions do not depend on the production method but from a lacking quality management. It becomes obvious that other production methods, which are more accessible to automation, cannot be eliminated through the current problems in quality assurance.

The introduction of quality management will enable identifying and to quantifying the individual reasons for measurement and form deviations. If quality management were applied consequently enough so that a control of dimensional accuracy could take place after every production stage, measurement and form deviations could also be corrected. This could result in a considerable reduction of production costs.

In the assembly of curved panels qualitative defects of single components, which result from previous production stages, so far had to be compensated for. These adjustments and subsequent operations are avoidable and increase the time needed for the assembly of the sections considerably, which can be seen in fig.7. According to our own studies the man-hour effort in the production of this section is twice as high as in the production of the parallel central nave. The compensation of measurement and form deviations on the single components in the previous production stages could reduce this effort considerably

This paper will show how a quality management can work and how it helps to correct these deficiencies.

A well working quality management is closely linked to the detection of statistical data which is needed to identify the quality of the production process. This kind of process parameters are hardly ever applied in shipbuilding production although it is state of the technology in general mechanic engineering to describe long-term developments in manufacturing to guarantee, through these key data, a well timed intervention when process blockages develop. One reason for the lacking of these accompanying examinations in shipbuilding is certainly the small series number of produced ships. Therefore this paper will develop a system, based on the findings of “statistic process control” (SPC). It provides the opportunity to also have a system for the detection of process blockage available in shipbuilding which goes much further than only curved panel production. This paper will not focus on the series of the vessel under construction but on geometrically similar assemblies which show similar qualitative requirements.

Due to the mentioned problems of the shipyards the further development of a production procedure for curved panels only plays a minor role. Neglecting the potential for development of this domain of shipbuilding production the shipyards miss the opportunity to act upon the cost pressure of the international shipbuilding market. As already mentioned in the introduction in future the mass-percentage of three-dimensionally formed sections in ship hulls will increase. Those who are provided with the measures and methods to produce these sections in a high quality and with low cost expenditures will secure a competitive advantage on an international basis for themselves and for their business. Additionally, the gained know-how in the production of this challenging assembly will strengthen the shipbuilding location in the long term. In general the citation of the Japanese shipbuilding technologist *Miyazaki (1998)* is true for shipbuilding:

> *„Only those who know how to produce the three dimensionally formed sections of the bow and stern as well as of their transfer area in a high quality are proficient in shipbuilding“*

PROCESS CAPABILITY AS BASIS FOR PRECISE PRODUCTION

Measurement deviations and their causes

In the outcome the measurement software detected measurement deviations which could not have been caused by systematical measurement deviations because they were largely superimposed by incidental measurement deviations.

Incidental measurement deviations are caused by measurement deviations in single components of the structure and by deviations which result from the insufficient accuracy of the jig pillar during the assembly process.

Measurement deviations which arise from welding deformations can be compensated systematically in this production process and through shrinkage management.

Due to the overlap of random and systematic measurement deviations, at this development-stage of curved panel assembly, compensation is impossible.

The overlap of the partial measurement deviations is expressed in process capability as a statistic factor for the stability description of the production process.

Process Capability in Shipbuilding Production

To be able to make a statement on process spread and the condition of the process it is necessary to detect the process capability indexes c_p and c_{pk}.

The key data of the process capability index c_p and the critical process capability index c_{pk} enable the evaluation of the process with regard to the criteria “controlled” and “not controlled” respectively as well as “capable” and “incapable” [Fig. 6]. A controlled process is recognizable the fact that the detected average values of the examined feature do almost resemble the allowed values of the feature. If this is not the case the process is not controlled.

If the measurements show a huge spread around the average value the process has a wide spread. This spread is determined by the process capability index c_p. The evaluation of the examined single components and profiles reverts back to this diagram to be able clearly evaluate the result of production. Processes with a wide spread and with an unstable position lead to enormous efforts in adjust and subsequent work. [see Fig. 7].

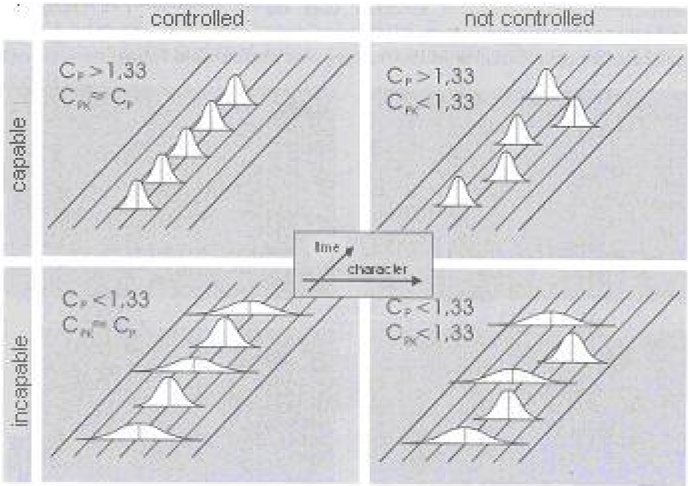


Fig. 8. Process spread and position against the process capability index, *Pfeiffer (1998)*

Mathematically speaking, the efforts in adjustments and subsequent work F_{auf} form a measurement for the deviations of the curved panel section to nominal dimension, required position and required design form (1).

$$F_{auf} = required - actual = \sum X_i \tag{1}$$

The process capability index c_p describes the relation of allowance tolerance T_{Norm} and process spread 6s, whereas s describes the standard deviation of the measured sample. If this ratio is bigger than or equals 1,33, a limit is reached which only requires little efforts in adjustments und subsequent work. For this approach the rest be equated with zero. According to equation (2)

$$c_p = \frac{T_{Norm}}{6s} \tag{2}$$

The process capability index c_p is indirectly proportional to the sum of deviations $\sum X_i$ (via standard deviation).

On the basis of this approach the effort for adjustments and subsequent work F_{auf} can be expressed with the help of process capability index c_p as such.

$$\frac{1}{c_p} \sim F_{auf} \cdot c_1 \tag{3}$$

c_1 represents a correction factor that considers the diverse cost structures per shipyard. With this technique, an effort for adjustments and subsequent work, F_{auf} , can be determined for every corresponding process capability index c_p. Consequently, this effort would be very large for a small c_p – value and very small for a c_p – value.

THEORETICAL BASICS

Tolerance Chain Approach

It is assumed that for the single components of structure single tolerances do exist, T_n , which are summed up to an overall tolerance T_0. Then, an additional final element S_0 which considers measurement, form and position deviations is introduced, see Fig. 8.

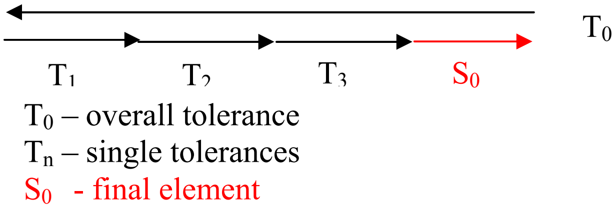


Fig. 8 Common theory of a solution for the tolerance chain problem

$$T_0 = (\sum_{n=1}^{n} T_n) + S \qquad (4)$$

According to this approach (4) the final element contains the deviations that divide into systematic and random deviations. Regardless of their origin the deviations are detected through measurements.

In general, a measurement (ME) essentially consists of the measured value (MW), the incorrectness δ and the unstableness u, which are then summarized signed through addition (5).

$$ME = MW - \delta \pm u \qquad (5)$$

It is presumed that with measurements taken under the same conditions incidental measurement deviations would occur as spreads and systematical deviations can be detected, *Pfeiffer (1998), Dutschke (1996)*.

But considering unknown systematic deviations and their treatment is problematic. This also applies to curved panels and will be further examined below.

Production Standards

To achieve comparability of the two approaches the production standards of German shipbuilding are applied. The functional tolerances are used as an evaluation standard for the yet to be detected process capability.

The following two production standards are available

- IACS „No. 47 Shipbuilding and Repair Quality Standard "–(Stand 08/1999), *IACS (1999)*
- VSM „product standard of German shipbuilding [external & internal part l], *VSM (1995), VSM (1989)*

PROCEDURE OF STATISTIC EVALUATION

Classification of Deviations in the Production of Curved Panels

Since the causes for the systematic and random parts of the deviations, according to „guideline for expressioning uncertainty during measuring", could not be strictly separated they will not discerned separately further. This declaration was made by the ISO workgroup and therefore it is binding, *Dutschke (1996)*.

Both parts of the deviations will be summarized in the instability u according to the equation 5. The incorrectness s is confined to well-known systematic deviations. But the systematic variations in the production of curved panels are unknown, because so far no mathematic solutions exist for these systematic deviations. The determining measuring result ME for the determination of the tolerances according to equation 5 only exists for the measurement value and the instability u. The incorrectness Δs can be neglected in the further considerations, because its part is constant and also cannot be changed.

The uncertainty of the measurement has the following parts:

- inaccuracy of the measuring instrument (systematic)
- subjective metering errors (incidental)
- deviations through welding deformations (systematic)
- deviations through application of the assembly (incidental)
- transformation of the coordinate system (systematic)

Since out of the measurement-results of the deviations of curved panel sections no definite parts of the overall deviation can be identified, all deviations have to be considered as instability of the measurement. According to *Dutschke (1996)* it is acceptable to assign 5% of the deviations to the inaccuracy of the measuring instrument, subjective metering errors and to the transformation of the coordinate system during the measurement evaluation. This distribution of the deviations should only serve as an approximation and is subject to certain variations depending on measuring conditions. Nevertheless, it is pivotal to know, that most parts of the instability of the measuring result have to be sought for within the deviations by applying assembly and welding deformations.

Selection of Appropriate Calculation Principles

Referring to *Nikolay (2002)*, the function of assemble-ability of Curved Panels in hulls determines the tolerance design. According to the state of the art, this functionality can only be afforded, if adjustments and subsequent work are conducted at the sections. The high requirements for dimensional accuracy resulting from the complete replace-ability can currently not be realized in shipbuilding. Therefore the *incomplete replace ability* was declared for the selection of calculation methods, *Dutschke (1996)*.

Hence, there are two possible calculation methods for the determining manufacturing tolerances:

- ➢ the probabilistic method
- ➢ compensation methods

Currently the compensation method is used by adapting and setting the assembly process in shipbuilding. To determine the production accuracy from measuring results of Curved Panels it is necessary to evaluate the measuring results with the probabilistic method. As a result of this evaluation it becomes obvious whether production tolerances can be derived from statistical determined production accuracies.

Procedure for the Process Capability Detection of Curved Panels

All objects examined in the following represent an extract from an amount of similar objects. Therefore the considered objects have to be regarded as samples of the respective basic unit. The statistic variables which are to be determined are valid for the following terms:

For the statistic evaluation the value of the sample ($\overline{X}$), standard deviation of the sample (s), the instability of the sample (u) and the confidence interval (K) are applied. All these variables are basic variables in statistics and their meaning is generally known.

With regard to one geometric feature the range of deviation is detected for all objects with the help of these variables. The following procedure is generally applied:

1. An amount n is determined from elements X_i, which describes a geometric feature
2. The average value of the sample $\overline{X}$ and the standard deviation of the sample s is detected from the amount n and the elements X_i
3. With standard deviation s and the amount n the instability u can be detected for a defined confidence level of 95% referring to *Dutschke (1996)*.
4. The confidence interval and its limits can be calculated with instability u and average value $\overline{X}$.
5. The range of deviations corresponds to the confidential interval at a confidence level of 95%.

However, the detected values are only valid for the sample. Furthermore an appropriate test needs to prove if these values also apply to the main unit. In another step of evaluation, statements concerning the quality of the results have to be made. This happens through the introduction of process capability indexes.

Further tests for the control of the significance of the sample for the main unit are the statistical weighting of measuring points, the outlier test and the test of significance. The outlier test applies to the procedure according to Grubbs, *Grubbs (1969)*. As the basis of the measuring a reference-system was defined which allows the target data and measurement results to be compared.[Fig. 9a]. The weighting of the measurement points is based on the different stiffness of the assemblies which lead to a division into two classes [Fig. 9b]:

factor 1	for all stiff frame and crossing points of the section
factor 0,5	for less stiff crossing points

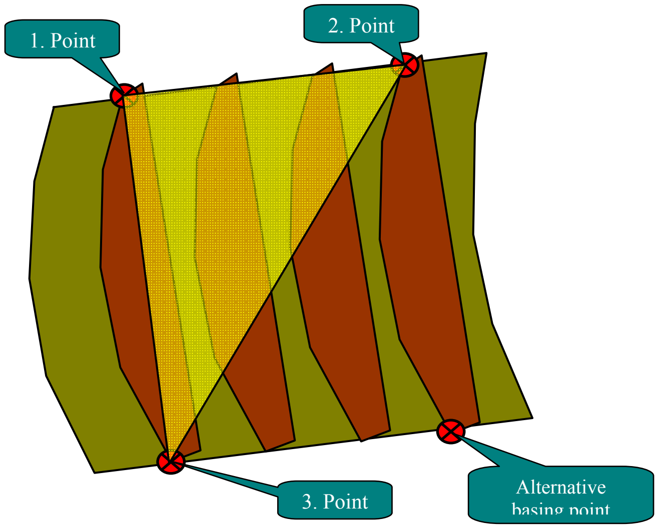


***Fig. 9a** New Definition of a reference – point – system*

The X^2 (Chi – Quadrat) test was used as a significance test. But if extremely small samples are taken this test may lead to misinterpretation, *Pfeiffer (1998)*. Therefore an extra test was developed.

From the determination of process capability indexes it is known that a relation of given intervals describes the process capability. In case of the process it is the ratio of given tolerance interval and sextuple standard deviation s, see equation (2).

If the ratios of the confidence intervals are formed of the samples K_s and confidence interval K_g of an amount of similar elements, the number n of which goes to infinity (which corresponds to the main unit), a statement on the adjustment of the sample to this infinitely large amount of similar elements can be detected. An expected zero hypotheses H_0 and a not expected alternative hypothesis H_A can be defined as follows:

$\mathbf{H_0}$	=	The confidence interval of the infinite amount of similar elements K_g applies to the confidence interval of the sample K_s. The sample is a part of the main unit.
$\mathbf{H_A}$	=	The confidence interval of the infinite amount of similar elements K_g does not apply to the confidence interval of the sample K_s. The sample is not part of the main unit.

If $\dfrac{K_s}{K_G} \geq 1$, the requirement is fulfilled. With that the lower limit is defined where the sample is significant for an infinitely large amount of similar elements. An upper limit cannot be defined clearly for this test.

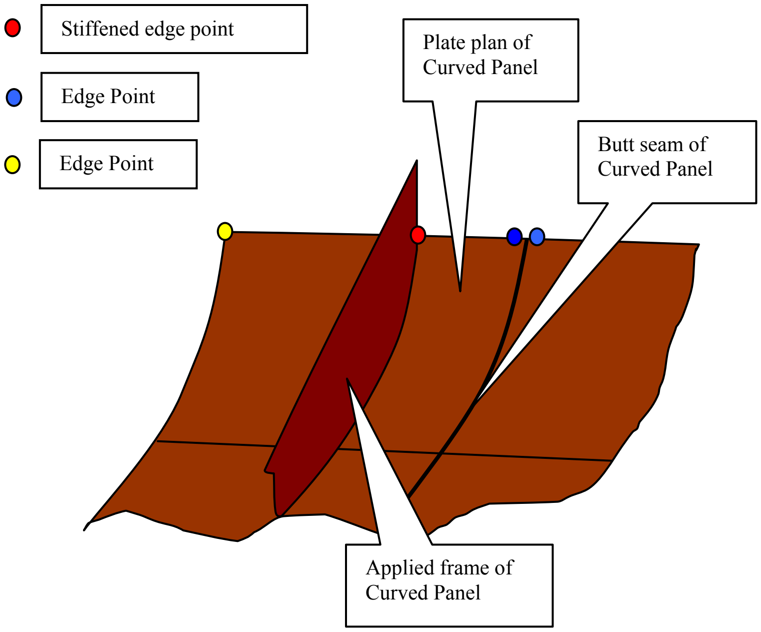


***Fig. 9b** Definition of the measurement point classes for curved panels*

However, this is not necessary because the lower limit clearly defines under which conditions the confidence interval K_g of the infinite amount is in the range of confidence interval K_s of the sample. This test is also regarded as a one-sided test because the condition for the fulfillment of the test hypothesis is always complied with the exceeding of the lower limit.

This test is sufficient for the examined objects because problems regarding too small samples cannot occur. At the same time this test is un-sensitive to deviations in normal distribution but yet sensitive enough to show deviations of the test hypothesis that the sample is a part of the infinite amount of similar elements.

According to *Dietrich (1998)* the **process capability index c_p** is determined by the ratio of given tolerance T_{Norm} and the sextuple standard deviation s. This range of sextuple standard deviation is also denoted as 6s – and indicates the process spread for 99,73% of all values, *Dutschke (1996)*. The characteristic, derived from equation 6, is called process capability index c_p.

$$c_p = \frac{T_{NORM}}{6s} \tag{6}$$

The lower limit of $c_p=1{,}33$ is also valid for this characteristic. An upper limit is not defined. In literature c_p values for capable processes can be found for a range of 1,33 to 1,67, *Pfeiffer (1998)*. In Asia (especially in Japan) even higher values ($2 \leq c_p \leq 5$) are given by experts.

The process capability index c_p expresses the process spread towards a given tolerance interval[Fig. 10]. In addition, it is considered preferable to describe the position of the process towards the tolerance interval. Therefore the process capability index c_{pk} is applied. The index c_{pk} can be calculated using equations from 7 to 9.

$$c_{po} = \frac{\overline{X} - T_o}{3s} \tag{7}$$

$$c_{pu} = \frac{\overline{X} - T_u}{3s} \tag{8}$$

$$c_{pk} = MIN\{c_{po}; c_{pu}\} \tag{9}$$

For the index c_{pk} the lower limit of $c_{pk}=1$ is also valid. If the c_{pk} value is above this limit the average value of the process lies within the tolerance interval. Otherwise the average value of the process lies out of the tolerance interval. If this is the case, the limit-values of c_{po} and c_{pu} have to be examined towards the bounds to detect the direction of the deviation. In *Pfeiffer (1998* the perfect position of process capability index c_{pk} is again given within the range of 1,33 to 1,67*)*. Within this range the average value of the process $\overline{X}$ and the average value of the tolerance interval are close together, the process is therefore not controlled.

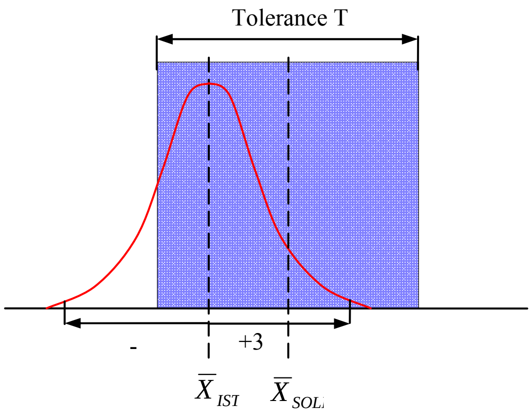


***Fig. 10** Position of the process spread against the tolerance*

Inspection of the process capability on the basis of selected examples

With process capability indexes of all sections average process capability indexes for every measured representative were formed [Tab. 3]. In doing so an average of all measured objects of respective representatives was made. With the help of these the performance of the production process can be determined. From this you can draw a conclusion concerning the necessary adjust- and subsequent works, shown in chapter 3.2. In addition, tendencies of accuracy-modification can be described by the process indexes of the production accompanying SPC. If there are initiate activities which lead to changes of the jig pillars, the effects on the accuracy of curved panels could be detected directly.

Furthermore, the critical process capability indexes c_{pk} were detected for all sections. With the detected c_p and c_{pk} values an evaluation of all sections in the portfolio after *Pfeiffer (1998)* [Fig. 6] is made.

Besides, the section's single components of the prefabrication were exemplaryly inspected. The result was that the process capability indexes of these assembly units only partially allow concluding to a stable process. The lacking process capability is a reason for the low values of the process capability of the sections.

If, in this case, the descriptive procedure is applied, production accompanyingly for the determination of process capability indexes (in terms of a SPC), the effects of technical – technological measures can be checked for production accuracy. Through the use of appropriate measures like advancing automation in prefabrication, an additional effect is expected in the stabilization of the curved panel production.

Tab. 3 Mean process capability index c_p and c_{pk} of the representative Sections

representative	Process capability index c_p	Critical process capability index c_{pk}
Crosswise stiffened	0,25	0,2
Longitudinal and crosswise stiffened	0,45	0,5
Longitudinal stiffened	1,05	0,9

MEASURES FOR THE STABILIZATION OF THE PRODUCTION OF CURVED PANELS

In the previous articles it is explained, how it was made possible to evaluate the production process of Curved Panels adequately, using two criteria and with the help of appropriate measuring equipment, a procedure, especially developed for this application, for the registration of measuring values and with a new concept for the statistical evaluation in the shipbuilding production. Consequently, it is possible to determine the capability of the process with the process capability index, which is known as potential process capability according to *Pfeiffer (1998)*. The critical process capability index indicates the level of controllability of the inspected production, which, according to *Pfeiffer (1998)*, is named effective process capability. The position of these two indexes expresses the quality of production process.

This was a first but important step for the stabilization of the production of Curved Panels. Subsequently, the results of these analyses have to lead to changes of the production procedures at the yards. Focused are the reduction of subsequent works and the expenditure of adjust- and subsequent works during mounting of the sections respectively.

During the inspection of adjustments and subsequent work it needs to be considered that these occur due to a manufacturing process with lacking stability. These works are an additional expenditure for the shipyard which cannot or can hardly be apportioned to the customer.

Another aspect to be taken into consideration is that these works almost entirely consist of manual working. Automatizing or mechanizing these workings is not possible, see Fig. 11. Consequently, this working is a potential threat for a stable manufacturing process.

In the following, it is described which methods enable to reduce these adjust and subsequent works.

Reduction of Adjust and Subsequent Works

The intent of this process is to avoid random, time consuming and hardly predictable adjustments and subsequent work as far as possible, to further improve the quality of steel-building production and to speed up the production process. In a first step this demands the systematization and the detection of efforts for all adjustments and subsequent work in every single production stage from single component to end product. Based on the knowledge about the current situation in the assembly of steel ship hulls as a result of these works it can be expected that the efforts in adjustments and subsequent work will decrease in every production stage. Therefore, it is imperative to realize adjustments and subsequent work on a module as early as possible in the production process.

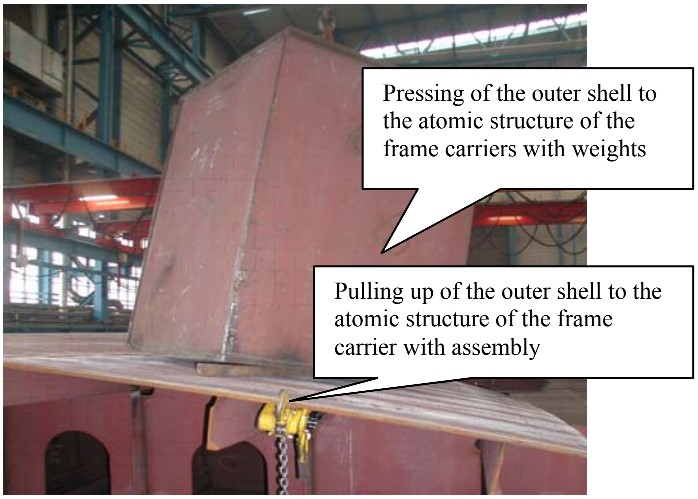


Fig 11: Example for adjustments and subsequent work on an overhead-built section

To solve this task the responsible persons in the shipyards have to realize that adjustments and subsequent work are not unchangeable parts of the shipbuilding manufacturing processes. Since these changes are linked to long processes of rethinking it helps to take other measures and methods which enable a faster reduction of adjustments and subsequent work. One option would be the introduction of a Statistical Process Control (SPC) which is linked to Quality Gates on the one hand and to the SIX – SIGMA method on the other hand. Both methods will be examined in the following.

Statistical Process Control (SPC)

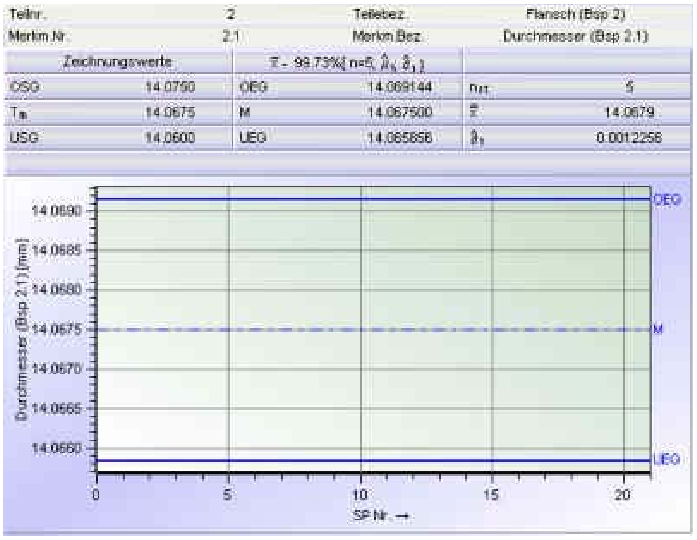
Statistical process control (SPC) is always part of an extensive quality management system. Quality control basically makes an essential distinction between two application ranges:

- Quality control of single products to eliminate rejected goods in case of manufacturing errors. This product control is often used in incoming inspections or in final acceptance of end products.
- Quality control for monitoring the production process. Samples from the running production are taken and controlled. If the products do not correspond to the standards the production process is set anew. This process control aims at the future quality of the product.

In process control it is assumed that there are incidental fluctuations in the quality of the product which are hardly manipulable or which demand another production process through higher automation. Moreover non-random systematic fluctuations in quality can occur, result from inaccurate regulations in the production process.

In above and at the beginning of this chapter it was pointed out that sufficient description of process fluctuations is given with the process capability indexes.

The detected process capability indexes have to be gathered on quality control cards and all deviations of the required position have to be documented on it.



Teilnr.	2		Teilebez.	Flansch (Bsp 2)	
Merkm.Nr.	2.1		Merkm.Bez.	Durchmesser (Bsp 2.1)	
Zeichnungswerte		$\bar{x}$ - 99.73%(n=5, $\hat{\mu}_s$, $\hat{\sigma}_1$)			
OSG	14.0750	OEG	14.069144	n_{ist}	5
Tm	14.0675	M	14.067500	$\bar{\bar{x}}$	14.0679
USG	14.0600	UEG	14.065856	$\hat{\sigma}_1$	0.0012256

Fig 12: Example of a typical quality regulation card

The quality control cards dates back to an invention made by the American W.A. Shewart in 1940. On these cards, the required position is defined as the average value, a maximum upper and lower action limit as well as upper and lower caution limits are included *Pfeiffer (1998),* see Fig.12. Today, sufficient calculative applications exist.

In addition to quality regulation cards for process capability indexes there are further values which can be detected. Standard deviations of the samples, which are detected on so called s-cards on the one hand and the spread of the samples recorded on R – cards on the other hand.

Regardless of the kind of recorded statistic parameters it is necessary to make connections between quality situations and used manufacturing methods. For that purpose the manner of the manufacturing process has to be documented accurately. In shipyards this is realized with the construction method. This method includes statements on:

- Geometric forms of the structure yet to construct
- The involved part structures
- Performing manufacturing tasks
- Application of material and additives

and on

- Performing measurement task for quality control

If both construction method and documentation of quality are given, a procedure, inevitably resulting in a change of the manufacturing process and leading to a stabilization of the manufacturing process, needs to be found. To achieve stabilization, the procedure has to include a cycle which includes the interplay of control and improvement as suggested by the Japanese model KAIZEN. A mechanism of action which supports the procedure and intensifies the procedure with its high requirements on the quality of the product is the SIX – SIGMA method which will be introduced in the next section. It defines this cycle as DMAIC, see Fig. 14.

Due to the specifics of shipbuilding manufacturing which is based on individual manufacturing a product control that rejects single products for reasons of substandard quality cannot take place in this case. The expenditures which are made during this procedure are contra productive for the goal of cost reduction. Only process control can be applied in this case but additional information on the stability of the process and on the efforts of adjustments and subsequent work at this precise object need to be given. This makes the shipyard capable of planning and controlling the application of employees and work equipment.

To design the process of quality control effectively positions have to be defined during production. Measurements should be taken and statements should be recorded just as seen in the figure above. On the basis of the application of SPC in other industries these positions are called „Quality Gates“. At these stages the decisions on rejections are made after product control. As already mentioned, this is not quite possible in shipbuilding manufacturing. The only possibility for the rejection of inaccurate products would be the production of single components. It has been pointed out above, that those inaccurate single components are one reason for measurement deviations in curved panels. It has been shown that the often instable production process in particular is often responsible for these deviations. A rejection of single components could increase the necessity of stabilization of the production process at this stage one the one hand and it could reduce adjustments and subsequent work in higher production stages considerably, thus resulting in a reduction of costs.

The realization of this SPC is, particularly in shipbuilding industry, linked to a number of difficulties because in many places adjustments and subsequent work are seen as an inevitable and basic part of ship production. To work against this a method is introduced below which is not only based on statistic results of the SPC but which is additionally integrated into business philosophy in a manner that will unavoidably encourage a process of rethinking among those who are involved .

SIX SIGMA practices in shipbuilding production

The lack of process capability in the manufacturing of curved panels forces the shipbuilding companies to take measures of quality assurance, which has not been used in shipbuilding before. Such a measure is the Six Sigma strategy.

As a result of the lack of process capability it comes to enormous efforts in adjustments and subsequent work to guarantee the connectivity of the section to the ship hull. This effort is reflected in a cost volume, which is not calculated in the costs of ship production primarily (as random) and therefore cannot be transferred to the sales profits of the ship. To achieve this effect, it is necessary to implement a strategy, which allows avoiding or minimizing not predictable, additional costs.

The application of Six Sigma strategy is very promising to stabilize the manufacturing process by introducing technological measures, so that the goal of cost saving can be controlled by statistical analysis. If corrections are necessary the production process may than be adjusted accordingly.

In order to maintain or increase the competitiveness of an organization, initiating improvements in business-processes is undoubtedly essential. Presently there are a variety of different approaches and philosophies for the process of continuous improvement (Kaizen, etc.). One of the latest campaigns is the Six - Sigma strategy. This strategy has proven to be impressingly successful in Japan and the USA and is now increasingly being implemented in European enterprises.

In Japan the development and application of consequent methods especially in precise production already started in the seventies. In the year 2000 single American shipyards started first studies on the application of Six Sigma in shipbuilding. In 2002 Northrop Grumman Ship Systems (NGSS) extended its Lean Production Program to a Lean Six Sigma Program with the support of the Advanced Maritime Technology Application Center (AMTAC) of the University of New Orleans (UNO). The departments included in the program were development, production and logistics processes as well as Supply Chain Management and finances.

When the Six Sigma strategy was introduced it was entirely focused on product quality. In order to easily sort the production-quality into a portfolio, as depicted in figure 13, process-capability indices have been determined on the basis of production-accompanying statistical process control. Processes with an insufficient process capability index ($cp \geq 1.33$; $cpk \geq 1.33$) are defined as the “weakest chain links” within the production chain, as far as quality costs are considered. A confidence interval of ± 3 σ is defined and the Six-Sigma-

Strategy goes even further by setting a confidence interval of ± 6 σ; a definition after which the strategy is named.

The standard deviation σ (Sigma) is a parameter of distribution functions measuring the variability of a certain quality characteristic compared to the expected value μ (Fig.13). The smaller σ, the smaller is the risk that a percentage of realization of a characteristic exceeds the specified limits.

If the process capability index cp rises at a given tolerance range, the process security rises. Striving to keep the production close to the tolerance centre will also result in a high critical process capability. This will cause product defects to decrease or even vanish completely.

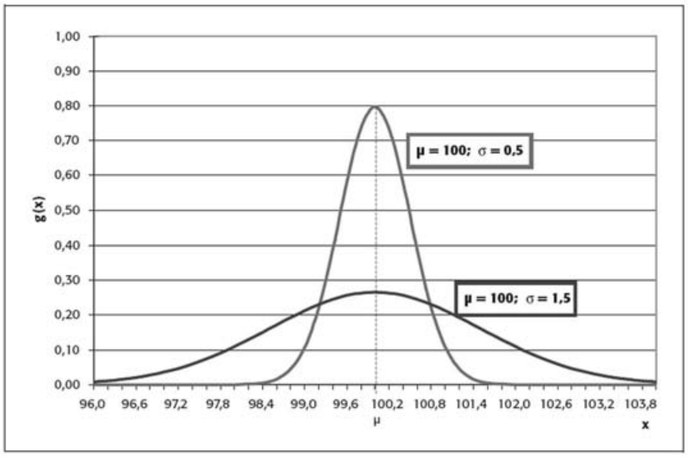


Fig. 13: influence of standard deviation σ on the form of the density function of the normal distribution of the features x

The term Sigma in its original sense only referred to manufacturing precision. In the framework of this strategy, Six Sigma means that in the short term one is able to produce with small deviations in such a way that within the tolerance range T there are exactly 12 Sigma units. This corresponds to a c_p-value of 2.0. This is already a very high quality requirement. If the expected value μ can also be held exactly in the middle of tolerance range (c_{pk} = 2.0), this includes the aim of "zero-defect production" (error share p = 0002 PPM).

This high production accuracy can even admit deviations from the average value of the tolerance mid without the risk of manufacturing faulty parts. The goal for the Six Sigma strategy is therefore $c_{pk} \geq 1.5$.

In case of excess of the error tolerance limits a process which recognizes and resolves the causes of problems will start. The impact of this process on the quality of the product is regularly reviewed and analyzed. This process, being called DMAIC, was also applied to business processes, which do not primarily influence the quality of the product. So the error limits were redefined and adjusted to the respective purposes. In the nineties, a powerful management tool was developed. Its effectiveness is especially based on its breakthrough method *Toepfer (2004)* to achieve basic external corporate aims. Since the DMAIC - circle must be applied continually, it is necessary for the staff involved to create motivations, which help the continuous leadership. On the basis of U.S. - American companies and their philosophies, the Green Belts and Black Belts were introduced.

This Green Belts and Black Belts are responsible for the consistent application of the strategy in their respective divisions. While the Green Belts control the process in the departments, the Black Belts summarize in general, evaluate and return appropriate measures to the Green Belts. This classification is modified with respect to the corporate hierarchy.

The first application of Six Sigma strategy in shipbuilding, took place in the U.S. Navy shipbuilding. The Northrop Grumman Ship Systems (NGSS) and the Advanced Maritime Technology Application Center (AMTAC) at the University of New Orleans were pioneers in this range. In the nineties, the lean management strategy was introduced, to meet the requirements of the U.S. Navy. Their basic problems were manufacturing errors, which in itself were small, but which lead serious consequences in the course of the assembly process. This "domino effect" called problem was the reason for the combination of the already introduced lean management strategy, which tries to avoid unnecessary processes, and the Six Sigma strategy *Radovic (2004).*

The interaction of both strategies leads to the immediate detection and remedy of errors during the production step. Since the errors (for example in plate production) are removed there, they cannot influence further production steps.

In the other manufacturing steps (for example section assembly), only those errors have to be eliminated, which also occur there. This leads to a reduction of adjustments and subsequent work in the advanced manufacturing levels and to an increase in the adjustments and subsequent work in pre-fabrication.

However, pre-production usually has a higher degree of automation or an easier automation handling, so that local manufacturing errors can be avoided by the consistent implementation of Six Sigma strategy.

This results in a cost reduction for adjust and subsequent work. The savings are made in the following aspects:

- Alignement of the assemblies
- Increasing the speed of the process by avoiding
- additional
- Reduction of welding work
- Reduction of subsequent work through higher quality

In addition, organizational problems in production such as lacking crane availability were examined. These investigations are still continuing *Radovic (2004).*

Besides that however, there are also additional costs that come with the introduction of the Lean Six Sigma strategy, resulting from training the professionals, communication needs and the manufacturing costs of additional manufacturing equipment.

A result of the requirements for the shipbuilding industry to compete with the prices of the East Asian shipbuilding industry on the world market, and because of the unstable manufacturing processes identified in this paper, it is imperative to reach a significantly higher manufacturing precision by employing new strategies in assembly processes. The Six Sigma method can certainly help to achieve this objective.

The basis of improving manufacturing precision in the assembly of curved panels is the introduction of a production-accompanying quality management. This quality management is based on the key element of Six-Sigma, the DMAIC-circle, which is being introduced in Fig. 14. There the curved panel production is taken as an example for the application of the DMAIC-circle.

Being the first DMAIC-element, D-Define, defines both the amount and goal of the investigated production characteristics. In this case it is the manufacturing accuracy of curved panels to minimize the dimensional deviations and the efforts for rectifications and correction work when the panels are mounted on the ship. To reach that it is necessary to introduce a production-accompanying measurement-program, M-Measure, that defines when and how the single measure-points are to be read. Additionally, the measuring-results are being evaluated and summarized by means of a statistical process analysis (e.g. control cards). The introduction of international shipbuilding contains the description of an applicable procedure for shipyards.

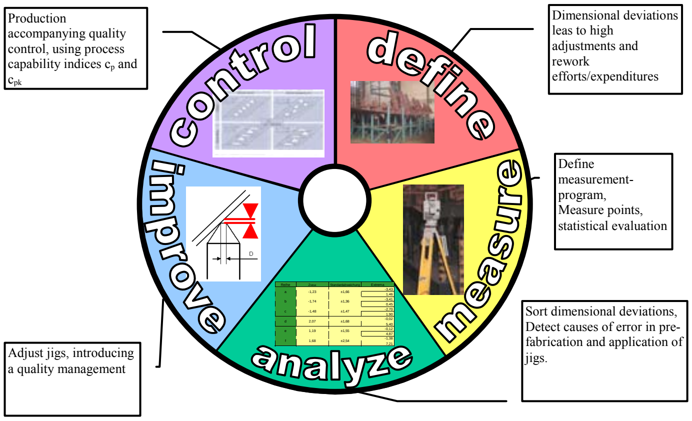


Fig 14: Application of DMAIC in curved panel production

In the next step the measurement-results are to be analyzed (**A - Analyze**). Measurements help to determine when errors in the production process occur, the causes of which are then to be detected. Within curved panel production these causes are to be found in the pre-production of single components (insufficient manufacturing accuracy) and the partially improper jigs as well as the mishandling of these jigs.

Based on these causes of error possible improvements (I-Improve) are derived. They may comprise changes in system-hardware (jigs) as well as introducing measures to reduce those causes of error that originate in the section pre-manufacturing (e.g. incoming goods inspections within the assembly process of curved panel sections).

As the last DMAIC-element, C-Control has to be interpreted as a further check of the introduced measures

Suitable test methods are selected to immediately identify deviations from the optimal process behavior. Within curved panel production the process capability indices cp and cpk are used as a control measure

By employing this control circle a continuous improvement of the manufacturing accuracy, like KAIZEN, will ensue. Due to the technological and technical preconditions on most shipyards it will probably prove impossible to fulfill the sharp Six-Sigma requirements. However, applying these rules may contribute to a considerable improvement in production capability.

With a stable production process it is possible to further increase production accuracy by employing measures to compensate for systematic dimensional deviations.

Introducing a quality management is both the most important measure as well as the basic precondition for the application of Six- Sigma. This measure is made feasible by introducing a measurement-program and a procedure for the statistical evaluation and analysis.

In the course of this paper a production-accompanying measurement-program for the assembly of curved panel has been defined. Causes of error for insufficient process capability have been discovered by a statistical evaluation and analysis, wherefrom measures to stabilize the production may be derived.

The devices used in curved-section assembly have to be redesigned to be able to guarantee form- and dimensional accuracy of the mounted outer-shell-panels.

Inaccurate single-components that contribute significantly to the instability of the production process have to be either excluded from the process by an incoming acceptance test or sent back to pre-fabrication.

Automatizing the curved panel assembly and pre-fabrication will contribute to lowering the error-rate according to Six-Sigma. A concept for this automation-process has to be developed with respect to the capability of the prospect user.

As a result of implementing these measures, the production process will be stabilized, reducing the random and hard-to-control-errors. By employing a program for reducing dimensional deviations similar to the "shrinkage manager"; *Heinemann (1999)*, the remaining errors could be reduced further.

A fall of the error-rate is to be expected of a consistent realization of these measures. However, still the strict failure-tolerance limits of Six-Sigma will hardly be achieved in shipbuilding but gross deviations and thus rectifications and rework will be made avoidable.

SUMMARY

With currently applied shipbuilding techniques it is still necessary to use additional allowances etc. to compensate for inaccuracies in dimension as well as form and position of components with a biaxially-curved surface. This results in rework and adjustment efforts. A successful introduction of precise-production for the basically orthogonal central-nave demands the possible introduction of precise-production for the transitional areas, bordering the stern- and bow-section, to be investigated also. However, this will not be possible until the production process is stabilized.

In order to support this stabilization it is pivotal to employ production-accompanying measurements and statistical evaluations. The resulting process-capability-indices cp and cpk, utilized in a statistical process control (SPC), serve to continuously improve the fabrication-accuracy by means of technological measures, the results of which are then again to be documented by the process capability indices. As a result, the ensuing circle of improvements in production-accuracy leads to a minimization of random dimensional deviations. The remaining systematic deviations may then be compensated in the course of precise-fabrication in shipbuilding.

Consequently, the shipyards ought to acknowledge having to sufficiently adapt the quality management of curved-panel-production as well as the importance of process capability indices for a stable production, which has already happened in various other industries.

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