UDC 629.5:658.5

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A Differentiation-Based Approach to Quality Management in Shipbuilding Taking into Consideration Errors in Manufacturing Processes

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Received (Primljeno):2012-10-22
Accepted (Prihvaćeno): 2013-01-15
Open for discussion (Otvoreno za raspravu): 2014-12-31

Professional paper

With conventional quality management methods and techniques used in repetitive projects it is possible to establish an efficient quality management and quality improvement system. The more efficient the system, the easier it is to identify points where errors are likely to occur and eliminate their consequences. Taking into consideration the fact that, as a rule, a shipyard is a large business system, with the present state of the Croatian shipbuilding industry it is very difficult to establish an efficient quality management and improvement system which can work effectively and permanently at all the stages of the production process.

With a differentiation-based approach to quality management, and by taking targeted corrective and proactive actions in the identified points of the manufacturing process in which errors are likely to occur, a certain improvement is achieved. The extent and duration of such an improvement depends on numerous factors within the system itself as well as on environmental factors. The improvement achieved with a differentiation-based approach is an incentive to take further quality improvement measures in a shipyard.

Keywords: *achieved excellence, points where errors are likely to occur, quality cost, risk of error, vertical differentiation*

Diferencijacija upravljanja kakvoćom u brodogradnji s aspekta pojavnosti pogreške u proizvodnim procesima

Stručni rad

Primjenom klasičnih alata i tehnika upravljanja kvalitetom u ponavljajućim projektima moguće je uspostaviti učinkoviti sustav upravljanja i unaprjeđenja kvalitete. Očekivani rezultat takvog sustava bit će upravo proporcionalni s prepoznavanjem točaka pogodnih za pogrešku i otklanjanjem posljedica koje one prouzrokuju. S obzirom na činjenicu da su brodogradilišta, u pravilu veliki poslovni sustavi, uspostava cjelokupnog učinkovitog sustava

upravljanja i unaprjeđenja kvalitete, koji bi permanentno djelovao u svim točkama proizvodnog procesa bila bi teško provediva u aktualnom trenutku hrvatske brodogradnje.

Diferenciranim pristupom upravljanja kvalitetom, odnosno ciljanim korektivnim i proaktivnim djelovanjem u prepoznatim točkama proizvodnih procesa u kojima nastaju pogreške, postižu se određena poboljšanja čije je vrijeme trajanja i stupanj poboljšanja uvjetovano brojnim čimbenicima okolnosti i sustava. Rezultati, odnosno poboljšanja dobivena provedenom diferencijacijom, predstavljaju osnovu za poduzimanje daljnjih mjera unaprjeđenja kvalitete u brodogradilištu.

Ključne riječi: *dostignuta izvrsnost, rizik pogreške, točka pogodna za pogrešku, trošak kvalitete, vertikalna diferencijacija*

1 Introduction

Quality management in shipbuilding industry came to the fore in European shipyards only after Chinese shipyards opened up to the world market. State subsidies granted to Chinese shipyards and significantly lower labour cost than in Europe have increased the competitiveness of Chinese shipyards in the world market. That is particularly the case in building simple-design ships such as bulk carriers, container ships and tankers. The Chinese approach to shipbuilding has resulted in shutting down a large number of European shipyards. It has also encouraged restructuring of large shipyard co-operative societies, such as the ones in ex-German Democratic Republic and Baltic States, where restructuring consists in re-engineering business and production processes in order to improve the quality of the final product. Also, a new market-based approach to the manufacturing process has been adopted. It is oriented towards high-technology ship manufacture. On the other hand, there are shipyards such as those in Poland, Romania, Bulgaria and Croatia, which have not adapted to the new situation in the market on time and now they are trying hard to find a way to survive in the market.

The shipyards that have managed to keep an advantageous position in the new-building market and have gained a lot of experience in making high-quality competitive products have the following in common:

- Efficient management,
- Timely reengineering, and
- A continuous quality improvement process.

As a rule, quality improvement actions and methods are attributed to the following:

- Compliance with agreed and/or predetermined standards,
- Working discipline, and
- Insisting on establishing operational excellence and independence.

Most of the recent shipyard research projects dealing with quality management were targeted at establishing a full-quality system (based on various models) with introduction of preventive and proactive measures. Superintendants or quality surveyors were responsible for corrective actions. After they have identified an error, they take corrective measures. It is possible to make a quantitative cost analysis of a corrective action in terms of supervision or

control costs as well as nonconformity (defect) cost analysis. The amount of the cost arising from nonconformity can be analyzed as a ratio of the amount invested in quality assurance and the damage caused by an error.

Due to the cyclical nature of the projects carried out in serial production of ships, it is possible to make a comparison and a statistical analysis of the costs arising from nonconformity. In addition, differentiation can help to identify model manufacturing processes in order to adopt and evaluate quality assurance measures.

2 Differentiation of the quality management and improvement system in a shipyard

Due to a continuous manufacturing process in shipbuilding, especially in a serial production of ships, in quality management system projects it is possible to pay close attention to the stages in which there are increased nonconformity costs (C_N). Identifying the spots in which there are increased costs due to a nonconformity means identifying the spots in which those costs are generated. Identification of such spots requires not only being acquainted with the organization of the manufacturing process and the likelihood of occurrence of an error that causes a nonconformity, but also a differentiation-based approach to quality management focused on thus identified points in which errors are likely to occur [1].

A ‘point in which errors are likely to occur’ is a term coined from experience and implies a spot or a process with increased likelihood of incidence of defects. A ‘point in which errors are likely to occur ‘ is a point within a manufacturing process in which the risk of nonconformity with the set quality standards is higher than in other surrounding spots due to its particularities or due to past events. A ‘point in which errors are likely to occur’ is not a static term; on the contrary, it is a dynamic value that changes its position depending on technological complexity and on a number of internal or external factors.

2.1 Differentiation of the quality management and improvement system in a process organization

Quality management systems can be differentiated with regard to differentiation of the product for which those systems have been established. Products of the same type commonly differ according to the technological level of manufacturing and usability, which is a vertical differentiation, and according to their attributes, which is a horizontal differentiation. As horizontal differentiation comes to the fore in serial consumer products (colour, design, equipment etc. required in the market), it does not have a wide range of applicability in shipbuilding.

A vertical differentiation is applicable in shipbuilding because vessels can be significantly different. More complex projects usually require instalment of a larger number of elements, which requires a larger number of activities, more workforce, more suppliers etc. Consequently, quality requirements in such projects are much more demanding than in simple projects (such as barges), where only procedures and set standards must be complied with and there are no additional requirements. A simplified example of a vertical product differentiation in shipbuilding is shown in Table 1.

Table 1 **A vertical differentiation (process approach)**
Tablica 1 **Vertikalna diferencijacija (procesni pristup)**

Project	Technological Complexity Level	Quality Requirements	Grade
Special Purpose Vessels	High	Very demanding	High
Multipurpose Vessels	Medium	Standard	I
Specialized Vessels	Medium	Standard	II
Simple Design Vessels	Low	Standard	III

Table 1 shows that a vertical differentiation of products which depends on the level of technological complexity is the starting point for a quality management differentiation.

Consequently, in a process organization in a shipyard, in accordance with high quality product policy requirements, a quality management system is targeted at a high level of technological complexity products.

2.2 A differentiation of the quality management and improvement system in a project organization

For a modern shipyard it is more acceptable to have a differentiation of a quality management system carried out in a project organization which is adopted when the project is initiated and ends as soon as the project is completed. With this approach it is possible to do the following [1]:

- Take targeted action in identified ‘nonconformity generating spots’
- Adopt prevention measures,
- Adopt control measures,
- Create a chain of responsibility,
- Calculate nonconformity costs,
- Calculate project QMI costs, and
- Calculate total quality-related costs when the project is completed.

Details of measures that have been adopted and the project results are recorded and, as projects in shipbuilding are cyclical, data bases are created in order to estimate quality management costs in the next project.

Thanks to the project organization and the project-based approach to quality management in shipbuilding, a project is not analysed according to its technological complexity. Instead, a differentiation is done within the project itself. In that way external vessel properties which are present in a project organization are avoided and each newbuilding is approached in the same way.

Table 2 shows a simplified example of a vertical differentiation of quality management in a project according to the stages of the manufacturing process.

Table 2 **Vertical differentiation (project approach)**
Tablica 2 **Vertikalna diferencijacija (projektni pristup)**

Stage	Technological Complexity Level	Quality requirements	Grade
Sheet cutting	Low	Standard	III
Pre-assembly	Medium	Standard	II
Section assembly	High	Very demanding	I
Furnishing	High	Very demanding	I

In a newbuilding project the most demanding stage in terms of technological complexity is the section stage. That stage requires the highest level of knowledge, skills and ability. It is important to point out that at that stage special attention is paid to fulfilling set quality requirements and it is necessary to establish stricter survey controls. All the nonconformities that were not noticed in the previous stages come to light at this stage.

A further differentiation can be done at any step of the project cycle, i.e. at any stage of the manufacturing process. An example of a differentiation of the section assembly stage, which is the most demanding stage, is shown in Table 3 below.

Table 3 **A verical differentiation at section assembly stage (project approach)**
Tablica 3 **Vertikalna diferencijacija u fazi montaže sekcija (projektni pristup)**

Assembly Stage	Technological Complexity Level	Quality Requirements	Grade
Engine Room Area	High	Very demanding	I
Cargo Area	Medium	Standard	II
Superstructure Area	Medium	Standard	II
Bow and Stern Area	Low	Standard	III

As it is shown in Table 3, the engine room area is the most demanding area in terms of technical complexity. Therefore, in accordance with the previous analyses of vertical differentiation, this area has to fulfil more demanding quality requirements than the others, due to which a quality management and improvement system has to pay close attention to it.

A further differentiation refers to the elements that make up the engine room area and the activities related to their assembling. Table 4 below shows a simplified example of the engine room area elements according to the level of their technological complexity.

Table 4 **A vertical differentiation in the engine room area (a project-based approach)**
Tablica 4 **Vertikalna diferencijacija u fazi montaže sekcija (projektni pristup)**

Elements	Technological Complexity Level	Quality requirements	Grade
Pipes	High	Very demanding	I
Cables	Medium	Standard	I
Profiles	Medium	Standard	II
Sheets	Low	Standard	III

A conclusion can be drawn that a vertical differentiation according to the level of technical complexity shows that the most demanding stage of the manufacturing process in terms of technological complexity is the section assembly stage of pipe production in the engine room area. As increased technological complexity arises from demanding quality and grade requirements, a quality management and improvement system will be aimed at meeting the requirements and standards that have been set. A differentiated approach serves that purpose.

A simplified quality management project differentiation as described above is a starting point in establishing a quality management differentiating model.

However, apart from theoretical considerations, it is also necessary to conduct empirical research in order to confirm or reject the hypothesis on the advantages of a differentiation-based approach used in a quality management and improvement system.

This can be achieved by analyzing defects and nonconformities in previous projects, which provides relevant data to calculate the likelihood of occurrence of an error, or the risk, and to identify the spots in which the incidence of defects is higher than in other spots in the process. In that way targeted action can be taken in order to ensure the required quality.

2.3 Quality-related costs in a project

ISO 9004 [2] defines quality-related costs as costs which are mostly incurred by introducing a quality system, i.e. costs which are mostly incurred by nonconformity-prevention actions and appraisal actions as well as costs of internal or external auditing.

Quality-related costs can be practically observed as the sum of the costs invested in the quality management system and nonconformity costs:

$$C_Q = C_{QMI} + C_N \quad (1)$$

where:

C_Q – quality-related costs

C_{QMI} – costs of quality management and improvement system

C_N – nonconformity costs

Costs of Quality Management and Improvement System (C_{QMI}) include all the investments in the manufacturing process that need to be made in order to ensure a high-quality product or high-quality services. They include [3]: prevention costs (C_p), appraisal costs (C_a) and quality improvement costs (C_i).

1) *Prevention costs (C_p)* are the costs incurred in order to keep minimal failure and appraisal costs.
2) *Appraisal costs (C_a)* are the costs incurred by determining the degree of conformity with the quality requirements.
3) *Costs of quality improvement (C_{qi})* are the costs of improvement and innovation. These costs include innovation rewards, consulting services or commissioned studies.

Nonconformity costs include all the expenditures that occur in order to rectify identified nonconformities. They can be divided into the two following categories: costs of internal errors (C_{ie}) and external-failure-induced costs (C_{ef}).

1) *Costs of internal errors (C_{ie})* are the costs incurred by nonconformities detected before the product is delivered to the customer.
2) *External-failure-induced costs (C_{ef})* include the costs incurred due to defects detected after the product has been delivered to the customer.

The complex quality cost structure can be expressed in the following way:

$$C_Q = \sum_{i=1}^{n} C_{QMI} + \sum_{j=1}^{n} C_{NI} \tag{2}$$

Although projects in shipbuilding industry are mostly repetitive (cyclical) and usually carried out by the same project team within a given period of time, it can be assumed that in each subsequent cycle T_{QMI} costs of quality management and improvement system will be lower, and a continuous improvement system should lead to a decrease in nonconformity costs (C_N).

A conclusion can be drawn that quality-related costs include all the costs incurred by rectifying the detected errors as well as those incurred in order to prevent such errors. With quality-related costs useless actions are turned into useful ones, or the current actions are improved, which increases competitiveness.

3 Errors and a risk of error in a manufacturing process

As a manufacturing process is very complex and it is affected by a lot of factors, there is always a certain likelihood of occurrence of an error. The likelihood of occurrence of errors which might have certain consequences, either as reduced safety or additional costs, is a risk which directly affects the product quality. From a risk-based point of view, quality includes any activity that reduces the likelihood of adverse consequences or eliminates or minimizes the risk consequences. Risk generally includes any likelihood of damage or loss as a consequence of certain actions or events. A mathematical expression of risk definition from a technology-based point of view, in which risk R is equal to frequency f multiplied by consequence c, is shown in the expression (1) below:

$$R = f \cdot c \tag{3}$$

in which:

R – risk [loss/unit of time],

f – frequency [number of events/unit of time],

c – consequence [loss/average event].

If the risk can be identified, analyzed and evaluated, it is possible to monitor and control it and risk management can be established [4].

3.1 Factors that generate errors in a process

From the risk-based point of view, an error is an event the result of which is an unpredictable damage, loss or costs incurred on tangible assets (machines, equipment or profit) during a manufacturing process. It is important to point out that an error is an extraordinary event which occurs as a result of adverse effects of the internal factors and/or environmental factors [5].

An error occurs at the point in which adverse conditions turn from acceptable to unacceptable, i.e. when adverse consequences occur. The course of events of error occurrence i.e. the transition from acceptable to unacceptable conditions is shown in Figure 1 below.

Figure 1 **The course of events of error occurrence**
Slika 1 **Tijek slijeda nastupa pogreške**

The course of events that results in error occurrence begins with acceptable conditions which include danger (poor visibility, fatigue, defective tools, machine malfunctioning), but they are acceptable until the moment in which due to an initial impulse or an initial event the entire system is turned into an unacceptable state or the state of error [5].

In the manufacturing process errors can be generated by either external i.e. environmental factors or internal factors i.e. factors involved in the system [6].

1) *Environmental factors* are external factors which are not part of the shipyard itself, which can affect the process and generate errors. It is important to identify the ones which can have a major influence on nonconformity occurrence and monitor them constantly, keep track of their changes and detect patterns of change;
2) *Factors within the system or internal factors* are present within the shipyard itself. It is possible to affect them only if they are correctly identified and consistently presented to the management in order to have them eliminated. Those are primarily organizational factors, safety factors and technological factors, which need to be 'refreshed' and improved from time to time.

   Consequences that arise from errors within the process can be classified according to their magnitude into categories ranging from catastrophic to insignificant. Since a consequence is considered to be a nonconformity in an average event, in order to evaluate consequences it is important to identify major nonconformities as well as the number of events that the average is based on.

   A quantitative measure for nonconformities present in a consequence of an error within the process is a monetary unit. The damage which is a consequence of an error within the process can be the following:

- direct, which can be measured after the error has occurred and it can be measured by the number of nonconforming products,

- indirect, which can be measured subsequently, after the repairs have been done and after considering the losses incurred due to delay, lost profit, increased insurance premiums, compensation claims and other claims that may arise from the errors in the process.

Errors in the manufacturing process occur with a certain frequency (f), the consequence (c) of which is a nonconforming product. The magnitude of the consequence (c) is multiplied to obtain the risk of error in the process. Therefore, the value of the risk (R) depends on the value of the consequence (c).

3.2 Characteristics of points where errors are likely to occur

In theory, an error can occur at any point in the process [7, 8]. In practice, however, in some segments of a manufacturing process errors are more common than in others. An error that occurs in a manufacturing process is caused by human activity the consequence of which is a nonconforming product. This definition of the error rules out the possibility of the process itself to be the cause of an error, which derives from the hypothesis that all the processes in a cyclical project are defined by proven technology. In addition, errors caused by machines, robotics or automatism are considered to be human errors caused by improper handling, poor maintenance or bad programming. In order to analyze a human error several methods can be used, ranging from a simple checklist of human factors to more systematic (step by step) analysis of human actions, to very sophisticated analysis of human reliability [9]. In such an analysis special attention is paid to determining and eliminating the circumstances in which human error causing nonconformity is likely to occur.

As points where errors are likely to occur change over time and space, the accompanying risk also changes, ranging from acceptable to very high. This range can be expected in areas with high technological complexity, high quality demands and first class quality demands. Therefore, it is important to pay special attention to the following [10]:

- the frequency and number of points where errors are likely to occur,
- the danger that arises from the points where errors are likely to occur,
- the amount of risk in the identified points,
- how certain the error is, why kind of error it is,
- possible consequences,
- the amount of time required to repair the damage in case of error.

The awareness of the presence of points where errors are likely to occur does not make a manufacturing process unstable. On the contrary, very often the awareness of the presence of such points affects the participants in the process as a warning increasing their alertness and readiness to respond promptly to a potential error.

4 An example of a point where errors are likely to occur

The consequence of an error in the process is a nonconforming product, which is the only possible way of measuring the error. As nonconformities are usually detected after a particular manufacturing stage is finished – during a control survey, the relative frequency of nonconformities will certainly be viewed as an *a posteriori* probability.

In a project-based approach nonconformities are detected in the milestones, i.e. the points in the project in which certain stages are being finished and passed on to the next project stage or to the customer. The project-based approach makes it possible to identify the error risk in the milestones as reference points that the project outcome depends on.

As it has already been elaborated above in Chapter 3, in a differentiation-based approach to quality management a manufacturing process should be monitored throughout the entire project life cycle, focusing on the technical complexity of the process, quality and class demands.

An example of a point in which an error is likely to occur in a ship pipeline manufacturing process

Ship pipelines are manufactured at all the stages of a newbuilding project life cycle. The incidence of errors depends on the technology used in shipbuilding. In traditional technologies pipelines are installed in the ship in subsequent project stages, whereas the modern approach to shipbuilding, in modules or sections, prefers installing pipelines equally at all the stages of the process.

Regardless of the ship pipeline technology that is used, it is acceptable to determine five milestones or reference points where it is necessary to survey the quality of what has been done in the previous manufacturing stage, as shown in Figure 2.

Figure 2 **Milestones in a newbuilding ship pipeline manufacturing process**
Slika 2 **Miljokazi u procesu izrade brodskih cjevovoda u projektu novogradnja**

I. *Pipe manufacturing* can be performed by machines or manually, automatically, semiautomatically, or in a classical way, and it consists of the following basic operations: cutting to size, bending, welding, labelling etc.
II. *Manufacturing process of testing workshop pipe connections* is performed by machines or manually, automatically, semiautomatically or in a classical way, and it consists of the following basic operations: water, air or oil pressure testing, ultrasound or x-ray connection testing etc.
III. *Manufacturing process of corrosive pipe production* is performed by machines or manually, automatically, semiautomatically or in a classical way, and it consists of the following basic operations: blasting, galvanizing, chemical treatments, colouring etc.
IV. *Manufacturing process of pipe installation* is performed by machines or manually, automatically, semiautomatically or in a classical way, in circuits, modules, sections or on the ship, and it consists of the following basic operations: transportation, assembly, flange connecting, welding, gluing etc.
V. *Manufacturing process of final pipeline pressure testing and delivery* is performed by machines or manually, automatically, semiautomatically or in a classical way, and it

consists of the following basic operations: water, air or oil pressure testing, ultrasound or x-ray connection testing etc.

As after one manufacturing stage is finished the workpiece is passed on to the next stage, it is necessary to carry out a control survey to determine the quality of the product which is being passed on to the next stage for further processing. As a rule, it is carried out in the following four ways [1]:

1) The control survey of a workpiece is carried out by the organizational unit that has manufactured the workpiece. This way is acceptable in highly automated plants where the amount of human labour is insignificant. It is subject to subjective assessment;
2) A control survey can be carried out when a workpiece is being taken over by the organizational unit at the next stage of the manufacturing process. It is common with products which require a large amount of human labour. The purpose of such a control survey is more to absolve from responsibility than to improve quality. It is also subject to subjective assessment and it is a frequent cause of conflict situations;
3) A control survey is carried out by quality management system control surveyors randomly, according to a plan, on a regular basis or on special occasions. This kind of a control survey is efficient in a process organization and in serial production. With time it becomes a routine, quality improvement diminishes and it becomes a regular control survey with repressive measures;
4) The fourth kind of quality control survey, which is very frequent in projects, is carried out by independent, mobile quality management teams. It is carried out in the points with an increased risk of error. One of the tasks of the teams is to determine the consequences of the error and the consequence costs. This kind of control survey is efficient in a project organization, especially in cyclical projects, where due to previous experiences it is possible to focus the activities on the identified points where errors are likely to occur.

It is important to point out that the fourth kind of control survey does not exclude the first three kinds. On the contrary, using the results of the other kinds of control surveys the mobile team can identify the causes of error and they can take measures in order to eliminate the errors. Even though the team consists of experts on technology, quality, safety and costs, they cannot be well acquainted with all the processes involved in a newbuilding manufacturing project. Therefore, the measures that the team may take in order to eliminate errors and to improve quality of the manufacturing process are aimed at reducing or eliminating the consequence cost. The way in which the consequence cost will be reduced or eliminated is left to the head of the manufacturing process with clear deadlines and determined amounts.

In a project it is possible to set an indefinite but final number of milestones ($Mk_{1\text{-}n}$), which depends on the complexity of the project as well as on its duration. As nonconformities or consequence costs can be detected in reference control points (milestones), it is clear that the error occurred at the manufacturing stage preceding the reference point in which the error itself was detected.

A milestone as ‘the point of final pressure testing and delivery’ is the key indicator of nonconformities. That is the point in which all the imperfections that occurred in the manufacturing process are revealed and assigned to particular manufacturing stages assuming that the entire manufacturing process, from the beginning until the end, has been properly

documented, according to requirements. Detected nonconformities that are the consequence of errors that occurred at the project stages that precede the manufacturing stage are not assigned to manufacturing stages but to previous stages.

Indicators of points where errors are likely to occur in a particular manufacturing process are the following: (1) frequency of nonconformities and (2) costs incurred by such nonconformities – consequence costs. As the frequency is multiplied by the consequence to get the value of the risk, the point where errors are likely to occur can be considered to be the location of a risk of error. Indicators of points where errors are likely to occur in a manufacturing process are shown in Table 5.

Tablie 5 **Indicators of points where errors are likely to occur**
Tablica 5 **Pokazatelji točke pogodne za pogrešku**

Process	Process area	Process duration	Number of nonconformities	Nonconformity costs
Pipe manufacturing	$Mk_0 \rightarrow Mk_I$	t_I-t_0	n_I	$C_{N\,I}$
Workshop testing	$Mk_I \rightarrow Mk_{II}$	t_{II}-t_I	n_{II}	$C_{N\,II}$
Corrosion protection	$Mk_{II} \rightarrow Mk_{III}$	t_{III}-t_{II}	n_{III}	$C_{N\,III}$
Assembly	$Mk_{III} \rightarrow Mk_{IV}$	t_{IV}-t_{III}	n_{IV}	$C_{N\,IV}$
Final testing and delivery	$Mk_{IV} \rightarrow Mk_V$	t_V-t_{IV}	n_V	$C_{N\,V}$

Table 5 and the mathematical expression of risk show that the risk of error in each process stage can be calculated in the following way:

$$R_I = \frac{n_I}{t_I - t_0} \cdot \frac{C_{N\,I}}{n_I} \quad \text{i.e. } R_I = f_I \cdot c_I ; \tag{4}$$

$$R_{II} = \frac{n_{II}}{t_{II} - t_I} \cdot \frac{C_{N\,II}}{n_{II}} \quad \text{i.e. } R_{II} = f_{II} \cdot c_{II} ; \tag{5}$$

$$R_{III} = \frac{n_{III}}{t_{III} - t_{II}} \cdot \frac{C_{N\,III}}{n_{III}} \quad \text{i.e. } R_{III} = f_{III} \cdot c_{III} ; \tag{6}$$

$$R_{IV} = \frac{n_{IV}}{t_{IV} - t_{III}} \cdot \frac{C_{N\,IV}}{n_{IV}} \quad \text{i.e. } R_{IV} = f_{IV} \cdot c_{IV} ; \tag{7}$$

$$R_V = \frac{n_V}{t_V - t_{IV}} \cdot \frac{C_{N\,V}}{n_V} \quad \text{i.e. } R_V = f_V \cdot c_V \tag{8}$$

When risk of error at different manufacturing stages is calculated, it can be compared with the risk of error in the equivalent stages in the previous projects. The risk of error at a particular manufacturing stage which is higher than the average indicates that at that particular manufacturing stage the risk of error is higher than in other equivalent stages, i.e. it indicates that there are points in which errors are likely to occur.

Nonconformity costs are identified in milestones for a previous manufacturing stage. Nonconformity costs consist of the basic value or excellence achieved in the past, which is the initial value, which should then be acted upon by the quality management and improvement system in order to reduce or eliminate the costs. The basic value is the 'achieved excellence' (AE), and its value is the cost of achieved excellence – CAE, i.e.

$$CAE = \min C_N \tag{9}$$

When nonconformity costs are higher than CAE, i.e. when there are increased costs in consequence of an adverse event or an omission, there are consequence costs – CC. Once achieved excellence in a particular point of the manufacturing process, it becomes a reference excellence for that particular point. Once achieved CAE cannot increase, it can only decrease. An example of achieved excellence and consequence costs is shown in Figure 3 below:

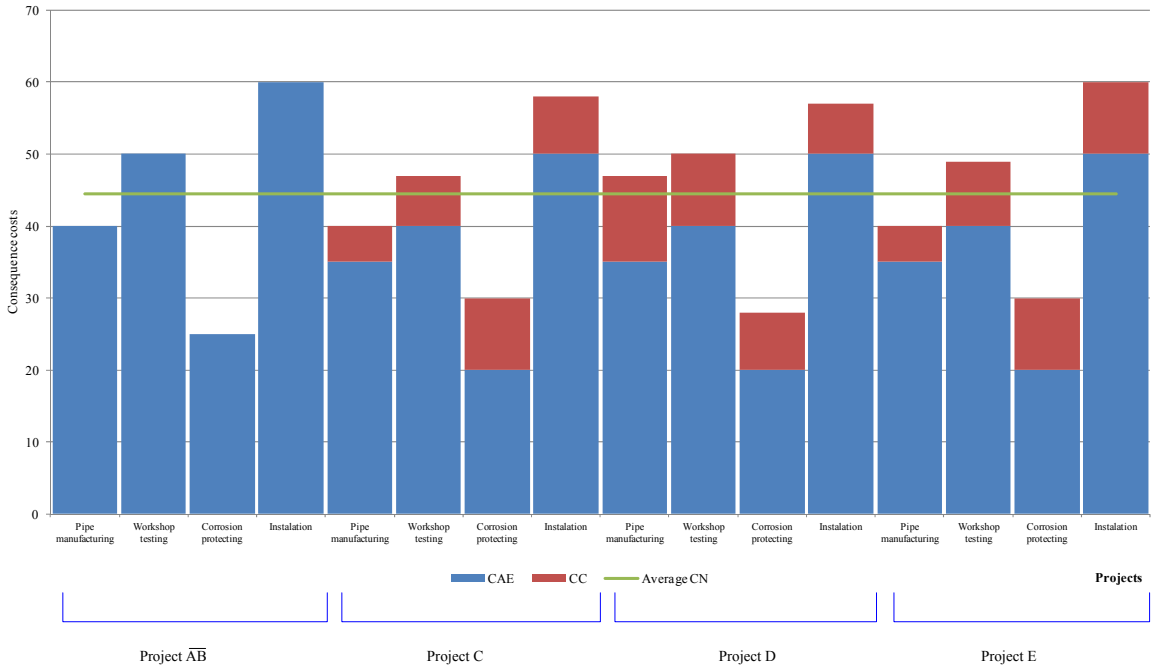

Figure 3 **An example of achieved excellence and consequence costs**
Slika 3 **Načelni prikaz dostignute izvrsnosti i posljedičnog troška**

The sum of all the reference excellences in a manufacturing process is the achieved excellence of the entire manufacturing process. The sum of all the achieved excellences of all the manufacturing processes is the achieved excellence of the project. Every subsequent project starts with the achieved excellence of the project but the quality management and improvement system aims at even lower values of CAE than those of the achieved excellence of the project and at setting new reference values.

A conclusion can be drawn that the aim of every new project is to cut CAE down to zero, i.e. achieve the so called "*zero defect*".

Regardless of how effective the control surveys at particular process stages are, there is still a number of nonconformities that remain undetected and are passed on to the next stage. Consequently, the final stage of 'final pressure testing and delivery of the system'

might have a relatively high achieved excellence and nonconformity costs because the nonconformities that have not been detected at the previous stages are detected at this stage. Therefore, it is important to set the maximum allowed value of such nonconformities which were undetected at previous stages and if they exceed the set value, it is important to re-examine the efficiency of control surveys at control points.

This final *stage is not considered* to be the point where errors are likely to occur. Instead, if it is not possible to decide at which stage nonconformities occurred, the value of detected nonconformities is successively added to previous stages in proportion to their size, according to proportional factor kK, which is a derived value directly proportional to the project stages.

Nonconformity costs in particular reference points of the process as well as in the milestones consist of the following:

$$C_{N\,I} = CAE_I + CC_I + kK_I, \tag{10}$$

and the total

$$C_N = \sum_{C_N=1}^{I=n} [(CAE_I + CC_I + kK_I)] \tag{11}$$

By monitoring the stages of pipeline manufacturing for a newbuilding 5 milestones have been defined and 12 control points in the manufacturing process. A conclusion can be drawn that with that number of control points no nonconformities can be undetected. In practice, however, that is not the case. Practical examples have been found in *BI 3.MAJ d.d.*, Rijeka shipyard. In other Croatian shipyards the indicators are very similar (insignificantly better or worse). The causes of such a case can be assigned to the following:

1) Control surveys are not 100% effective;
2) The costs are not equal to the damage;
3) Points where costs are increased have not been identified;
4) Points where errors are likely to occur have not been identified.

After nonconformity costs have been calculated for each stage of a manufacturing process, their average value is calculated as well as the standard deviation. Standard deviation is a measure to assess the variability of the nonconformity costs in the entire manufacturing process or at a particular stage of the manufacturing process.

The initial value of nonconformity cost is the lowest measured cost or the cost of achieved excellence. According to the definition, a point where errors are likely to occur is not static. In fact, if after some time a lower cost than the cost of achieved excellence is measured, either as the cost of the entire manufacturing process or the cost of just one stage in the process, the lower cost is considered to be the cost of achieved excellence.

6 Conclusion

With sufficient theoretical knowledge it is possible to identify the points where errors are likely to occur. The term itself, 'a point where errors are likely to occur', has been coined for research purposes in order to focus on the spots in the manufacturing process where there is a larger number of nonconforming products than in others, which leads to increased costs. In order to detect such spots it is necessary to carry out a differentiation of the quality management and improvement system in a process organization.

As each project is specific regardless of how cyclical it is, and has its own combination of internal and external factors affecting the established quality management and improvement system, a lot of effort is put in order to have nonconformities completely eliminated from the manufacturing process.

Shipyards are faced with increasing quality demands and strict product surveys in order to have a final product which fully meets the client's standards and demands. Therefore, the quality management and improvement system is faced with the problem of ever increasing control surveys, control surveyors, and quality management and improvement costs. For that reason shipyards tend to use a differentiation-based approach to quality management in order to focus on the causes of nonconformities and have a flexible and efficient quality management and improvement system.

Quality management systems are differentiated with regard to the differentiation of the product which they have been established for.

In a project-based approach to quality management in shipbuilding, a project is not classified according to its technological complexity. Instead, differentiation is carried out within the project itself. In that way external properties of a ship, which are dealt with in a process organization, are left out, and each newbuilding is approached in the same way. With a differentiation-based approach to the management system, which is adopted when the project is initiated and ends as soon as the project or a project lifecycle stage is finished, it is possible to take a targeted action against the detected points in which errors are likely to occur and establish adequate prevention and control measures, create a chain of responsibility and calculate nonconformity costs, the costs of the project quality management and improvement system as well as total quality-related costs when the project is finished.

With the data on the measures that have been taken and the results obtained a database is created which helps assess quality-related costs in a following project.

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