UNIUNEA EUROPEANĂ GUVERNUL ROMÂNIEI Fondul Social European POSDRU 2007-2013 Instrumente Structurale 2007-2013 MINISTERUL EDUCAȚIEI NAȚIONALE OIPOSDRU Universitatea Politehnica din București

Universitatea „Dunărea de Jos” din Galaţi

Școala doctorală de Inginerie

UNIVERSITAS GALATIENSIS

DOCTORAL THESIS

Summary

CERCETĂRI PRIVIND FENOMENUL DE COROZIUNE A CORPULUI NAVEI ÎN VEDEREA EFICIENTIZĂRII CHELTUIELILOR DE ÎNTREȚINERE ȘI REPARAȚII

RESEARCH ON THE CORROSION PHENOMENON OF SHIP HULL IN ORDER TO REDUCE THE COST OF MAINTENANCE AND REPAIR

Doctorand,

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Conducător științific,

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Seria I 6: Inginerie mecanică Nr. 33

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2016

Seriile tezelor de doctorat sustinute public în UDJG începând cu 1 octombrie 2013 sunt:

Domeniul **ȘTIINȚE INGINEREȘTI**

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Seria U 1: **Filologie- Engleză**
Seria U 2: **Filologie- Română**
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Keywords

- ✓ Corrosion
- ✓ Efficiency
- ✓ Cost
- ✓ Repair
- ✓ Maintenance
- ✓ suply Offshore Vessel
- ✓ maintenance and repair costs
- ✓ hull
- ✓ classification society requirements
- ✓ The evolution of corrosion
- ✓ Structural Analysis
- ✓ "Cost Efficiency Program"

Introduction

1. General topic and fields of interest

In the current international economic context, where the shipbuilding industry went into a visible decline, a viable solution is a decrease in the transportation costs of goods over water. These costs, together with the operational ones, also refer to current maintenance and repair costs. Ship owners are looking for a solution to increase the life duration of the ships in their possession. Therefore, beside the attention given to ship designing, choosing the on board and deck installations, a great interest is shown to the phenomenon that produces significant wear of the hull, this phenomenon being known as corrosion.

The subject under lens in this research has been a highly debated one ever since the creation of metallic structure vessels, but, at the same time, it is very modern because the problem of hull repair costs has not been completely solved. Therefore, there are still situations when, after a certain period of time following the start of the repair, the whole operation stops because during its development the costs are becoming too high compared to the initial ones. Under these conditions, ship owners tend to start building a new ship, the total costs being comparable to the ones needed for the repair of the used one.

The errors occurring in estimating the costs have harmful consequences in carrying out the activities, ship owners forcing the shipyards where the work is carried out to carry on with their actions, thus suffering losses. Therefore, in order to avoid these drawbacks, it is necessary to be fully aware of the degree of ware and of the work that needs to be executed, and then to have an efficient repair plan that matches the initial budget.

A possibly more important problem than the cost of repair works is that of ensuring the requirements of the classification companies from all points of view: general and local resistance, safety in navigation, as well as ensuring a decent living for the on-board crew. Satisfying the first two requirements is achieved by calculating the structures, having in view the reductions in plate and framework thickness caused by corrosion.

In order to achieve the purpose of the study, it was necessary to clearly set the objectives that subsequently lead to solving the problem of lowering the repair costs.

2. Context and objectives of the research carried out

In order to achieve the main goal, that of increasing the degree of efficiency for ship maintenance, and to provide vital and useful information referring to the nature of determinant factors, the studies will be concentrated on achieving the following main objectives:

- Investigating and evaluating the data referring to the influence factors in the occurrence and evolution of corrosion;
- Study of the calculus methods used in determining the rate of corrosion evolution;
- Presenting the technical aspects of the structural analysis by using the method of finite elements and applying them to the vessel that constitutes this paper's object of study;
- Achieving the structural analysis based on centralised measures, carried out by classification companies during the usage period, measurements that were performed every 5 years, its purpose being to graphically highlight the way in which corrosion influences the evolution of tensions and the area where the tensions have the highest value;
- Determining the area where the tensions have values close to the limit ones;
- Study of the influence of corrosion on the tensions and, implicitly, on the resistance of the vessel;
- Determining the actual costs generated by corrosion in the case of the analysed vessel from a structural point of view, and evaluating the results in view of determining the key costs. These are represented by variable costs which fluctuate according to certain factors, this characteristic offering the possibility to reduce the final cost;
- Establishing the procedures which must be had in view for analysing and identifying the optimal alternative concerning cost efficiency determined by the repair and maintenance;
- Determining the conditions under which the efficiency reaches a maximum level, and where the criteria requested by ship owners and classification companies are satisfied.
- Numerical processing of the experimental data – by simulating the combination of factors which are part of the total cost, in view of determining the optimal alternative.

Reaching maximum efficiency, as well as satisfying all criteria set by ship owners and classification companies are had in view. This is achieved by means of the electronic program presented this thesis – “Cost Efficiency Program” –, program whose purpose is to analyse and process a large volume of data, achieving their evaluation for all construction, maintenance and repair alternatives.

3. Approach and results

The doctoral thesis is structured into 7 chapters, as follows:

Chapter 1 presents the introductive notions, offers the motivation for choosing the research theme, mentioning the importance and significance of the subject. It then presents a description of the current stage of the study on the influence of corrosion on marine structures. It describes de factors that influence the occurrence and evolution of corrosion in general, in the naval field in particular, and analyses the necessity and opportunity of cost efficiency associated to hull maintenance and repair, from the perspective of corrosion – the central point of interest for the research carried out.

Chapter 2 presents a description of the corrosion evolution from a theoretical stand point, concerning the methods for the theoretical determination of the corrosion rate, defines the characteristics of hull corrosion models, as well as the fundamental approaches regarding hull corrosion models.

Chapter 3 describes the aspects of Finite Elements Method (MEF) in the structural analysis of the vessel as main study method and for establishing the tension in case of a newly built vessel. Moreover, a structural analysis of a supply vessel for offshore drilling platforms (offshore supply vessel OSV) is carried out, this type of vessel constituting the landmark of the entire study. This analysis is achieved to determine the area of study for the modifications in tension caused by corrosion. In this chapter, diverse calculus scenarios are addressed, all of which have determined the choice of dangerous areas and the modalities of determining hull tension.

Chapter 4 highlights the development of the tension state in time, on the interest area described in Chapter 3. In this chapter, based on the studies previously carried out, the structural analysis was carried out highlighting the effects of corrosion from the perspective of general and local hull resistance on the selected area. Therefore, after 20 years of vessel usage, the value of the safety coefficient for the value criterion surpasses the unit value, a number of constructive solutions thus being rendered necessary. The verification and validation of the constructive solutions proposed is then achieved, to be applied after a period of 20 years of vessel usage, through the analysis of tension evolution before and after the repairs are carried out.

Chapter 5 describes the current control and cost efficiency methodologies for ship maintenance and repair by presenting the efficiency concept and the importance of cost efficiency for ship maintenance and repair. The comparative study of the advantages and disadvantages in using the two cost efficiency procedures for repair and maintenance, namely optimization and simulation, has as a result the necessity of combining these two processes for designing an efficiency software useful to ship owners.

Chapter 6 presents the analysis of actual costs generated by corrosion in the case of a vessel analysed from a structural standpoint, and the results evaluation, in view of establishing the key costs in the process of efficiency building. Taken into consideration for modelling the process for determining a ship’s costs were the data obtained based on the structural modelling achieved in the 3D-FEM program presented in Chapter 3 of this thesis, and the registrations of the ship owner, carried out every 5 years and concerning the hull maintenance and repair carried out in the last 20 years.

Due to the complexity of the ship maintenance and repair costs analysis, an electronic program – capable to determine the optimal alternative having in view the multitude of parameters involved and offering the possibility of simulations for the entire life period of the vessel – was chosen.

Under these conditions, the situations in which the efficiency reaches a maximum level will be determined, and the criteria expected by the ship owners and by the classification companies are simultaneously satisfied. The numerical processing of the experimental data – by simulating the combination of factors which constitute the total cost, in view of determining the optimal alternative where efficiency is maximum – is achieved by means of an electronic program developed in this thesis: “Cost Efficiency Program”. This program can be used as support in decision making in relation to hull maintenance and repair in real time, for most types of vessels.

The final chapter, namely *Chapter 7*, presents the conclusions of the research activities carried out, highlighting the personal contributions, the dissemination of results and the future research directions.

In addition, the thesis has a number of 4 annexes which represent the source codes of the programs developed in view of improving the processes and determining the experiments carried out.

CHAPTER 1
Current state of the study on the influence of corrosion on marine structures

1.1 General aspects of metallic surfaces degradation by corrosion

1.1 General aspects of metallic surfaces degradation by corrosion

The negative effects determined by metal corrosion have preoccupied human society since ancient times. Corrosion consists in destruction – partial or total – of the superficial layer of metals, as a consequence of various chemical, electrochemical or biochemical oxidation reactions occurring during interactions with the environment [1-4]. Frequently, in its simplest form, corrosion is described as the rust cover of the superficial layers of the designed structures made out of different types of steel or other metallic materials. It is appreciated that the problems caused by corrosion in countries with a developed economy is up to 4-5% of the internal gross product. They manifest themselves under various forms. First of all, there are the direct irrecoverable losses of metal (approx. 10-20%). Therefore, the biggest losses are associated with the indirect consequences of corrosion, much more difficult to be appreciated at their real value [5].

CHAPTER 3
The Finite Elements method of analysing the structure of vessels
Determining the tension state for vessels newly released from the shipyard

3.1.1 Meshing of naval structures. Finite elements used in the structural analysis.

The main structure elements which are part of naval structures are bars and plates. As a consequence, the main types of finite elements used in the ideal structuring of a vessel are elements of the beam and plate type.

3.2 Determining the tension state in the case of a(n) (uncorroded) vessel newly released from the shipyard

3.2.1. 3D-FEM numerical analysis of the hull's local and general resistance

In view of carrying out the proposed research, a supply vessel for offshore drilling platform (offshore supply vessel OSV) was chosen as main study object. The construction data are from a 3300 OSV built at Damen Galaţi Naval Shipyard.

OSVs are equipped with tanks for transporting drilling mud, fuels, drinkable water or any other substance necessary on a maritime platform. These vessels are equipped according to the specific labour conditions and to the functions that they have to meet [78].

3.2.2 Analysed cases of loading

The numerical analysis using 3D-FEM models was achieved for two loading cases and for quasi-static equivalent rom 0 m to 6 m wave heights, both in wave peak cases, as well as in empty waves ones. The height of the equivalent quasi-static wave, determined statically, is of h_w = 5,840 m, according to Bureau Veritas [79]. The 3D-FEM model used for the numerical analysis was extended for the whole length of the vessel and was generated using the FEMAP/NX NASTRAN program.

Applying the loads is achieved by own user procedures [80] for: distributing the hydrostatic pressure of the equivalent quasi-static wave, as well as for distributing the hydrostatic pressure in tanks and the loads on decks.

The two loading cases analysed in the present study for the OSV are the full loading case and the ballast loading case.

3.3.5 Results on the analysis from the perspective of the OSV hull's local and general resistance

The numerical results of the hull general resistance analysis indicate:

- a maximum value of the safety coefficient for the yielding ratio was 0.878 in the junction area of the bridge main parapet and the exterior layer, in full loading case, equivalent quasi-static wave peak with a height of h_w = 5,84 m.

- a maximum value of the safety coefficient for the buckling ratio with a value of 0.812 for the bottom area, in ballast loading case, equivalent quasi static wave peak with a height of h_w = 5,84 m.

3.3.6 Analysis of the tensions which appear in the chosen area of interest

The study mentioned in the previous paragraphs was necessary for determining the areas where loss in equilibrium stability may appear (buckling of the plates composing the hull).

Figure 3.27 presents the distribution of the safety coefficient for the buckling ratio (BR) on the exterior layer, the structure of the new vessel. In the images below, may be observed that the interest area is the bottom one. These areas will be subsequently studied by applying the corrosion rates corresponding to the life duration of the vessel.

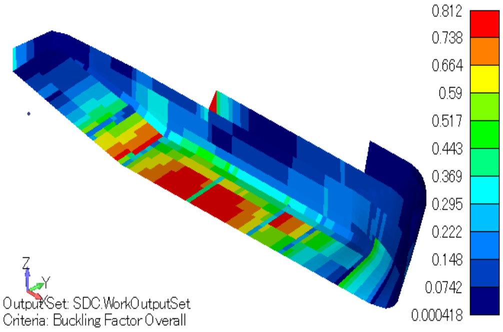

Fig. 3.27 BR distribution on the exterior layer for the analysed model, case of full loading, wave peak, h_w = 5,84m

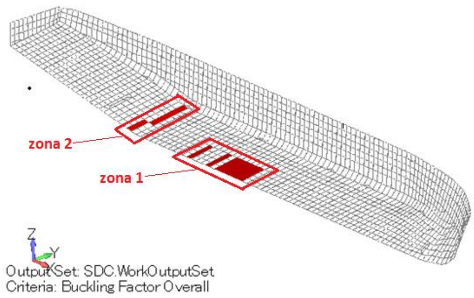

Fig. 3.28 The areas where the safety coefficient value for buckling is almost a unitary value

It may be observed that the value of safety coefficients is higher on the exterior layer in area 11-33 m. In order to analyse the influence of corrosion on the safety coefficients, the area of evaluation presented in figures 3.29 and 3.3., comprised between 11.05 and 33.80 m, was selected.

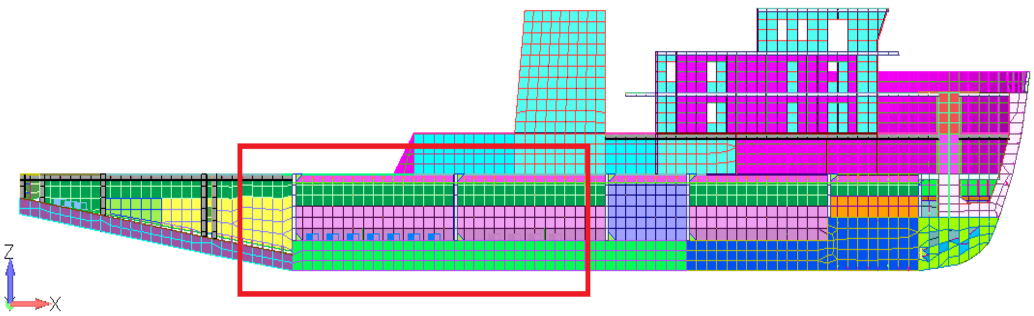

Fig. 3.29 3D-FEM model extended on the whole length of the vessel with the area selected for analysis

CHAPTER 4

Study on the variation of tension in the area selected for analysis

4.1. 3D-FEM numerical analysis of the corrosion effects from the perspective of the Offshore Supply (OSV) hull's local and general resistance in the analysed area

Modelling the marginal conditions and the distribution on masses based on the 3D-FEM model is closer to the real physical model of the hull; the equilibrium procedure in equivalent quasi-static meeting waves does not imply restrictions regarding the 3D-FEM model; the results obtained from the 3D-FEM models analysis allow the evaluation of 3D tension and of the deformations, highlighting the tension concentrators.

According to the measures achieved by the classification society [78], Table 4.1 presents the influence of corrosion on the structural elements of the master section of the OSV.

In the first 15 years of use, the value of the safety coefficients, both the flow safety coefficient and the fogging coefficient, are under the unitary value. For stage 4, where the corrosion has been applied on the structure of the vessel corresponding to the last 20 years of use, the corrosion effect over the exterior layer can be observed, as shown in the diagrams above – transposed in that the maximum values of the safety coefficient for the value criterion surpass the unitary value in the bottom area.

Case of full loading

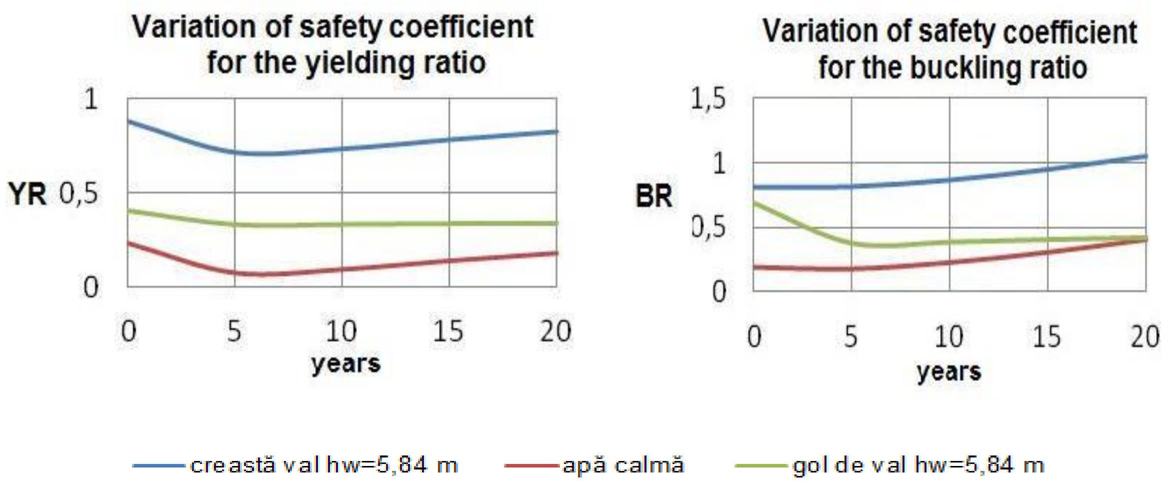

Fig. 4.9 Variation safety coefficient for the buckling ratio

Case of ballast loading

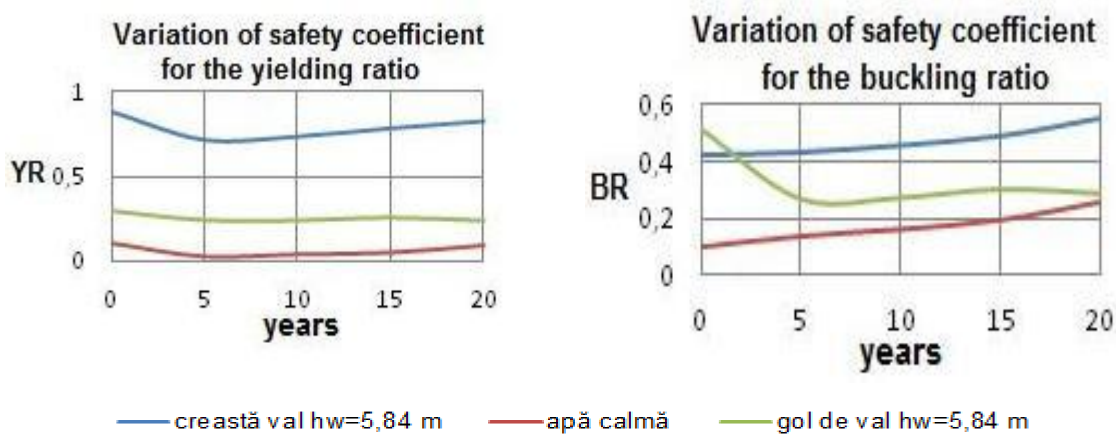

Fig. 4.10 Variation safety coefficient for the yielding ratio

The numerical analysis carried out on 3D-FEM models completely extended to the entire length of the vessel for demands in calm water and quasi-static waves allows the verification of the resistance criterion in connection to the flow limit of the material, and therefore determines the tension concentrations.

Figures 4.11 and 4.12, for the full loading case, and Figures 4.13 and 4.14, for the ballast case, show the influence of corrosion on the hull's general and local resistance. In time, due to the diminishing of the structural elements, the value of the safety coefficients increases for the flow and fogging criteria.

Therefore, after a period of 20 years of vessel use, the value of the safety coefficient for the fogging criterion surpasses the unitary value, the replacement of various plate strips on the bottom layer being necessary. Constructive solutions in this case are presented in Fig. 4.15 and Fig. 4.16. In the case of both areas, the adopted constructive solution is that of replacing the plates in the areas where the safety coefficient surpasses the value of 0.9. For area 1, the measurements of the plates that have to be replaced are 13 m x 3.3 m and for area 2 these are 2 6 m x 2.6 m.

CHAPTER 6
Applying efficiency and simulation procedures in view of reducing the costs generated by OSV hull maintenance and repair

6.1 Determining the initial UNOPTIMIZED cost of the OSV
6.1.1Initial analysis of the cost elements and of the total cost of the vessel

Determining the cost for the initial investment (for vessel construction)

In what follows, the calculation is made for determining the initial cost of the vessel using unoptimized procedures, and based on the data previously presented

Table 6.7 Calculus relations for the initial cost of the vessel

Name	Calculus relations	Price (eur)
Steel cost	$\Delta \times CC_i$	5.780.700,00
Deck Coating cost	$A_p \times CV_i$	37.842,00
Superstructure Coating cost	$A_s \times CV_i$	95.557,00
Hull coating cost	$A_h \times CV_a$	96.390,00
Thanks coating cost	$A_t \times CV_i$	122.998,00
Anode cost	$NA_i \times CIA_i$	7.013,00
TOTAL		**6.140.500,00**

Determining the repair cost of the anticorrosive protection

During the first inspection carried out after 5 years of vessel functioning, it was noticed that the deck had to be repainted because of the intense friction on loading and unloading heavy transported goods. This repainting procedure is necessary every 5 years to ensure protection to the over-solicited deck, according to the specifics of the vessel.

After the first five years, the repainting of the hull is no longer necessary, decision taken in conformity with the results of the technical inspection. Moreover, according to the verifications carried out during the 15 years inspection, it was observed that no repainting of the hull was necessary.

Tab. 6.8 Calculus relations for determining the repair cost of anticorrosive protection

Area/years	**Calculus relation**	**Cost of repair anticorrosive protection (eur)**
Deck		
5	$A_p \times RV$	67.257,00
10		73.935,00
15		48.402,00
20		93.810,00
Tanks		
5	$A_t \times C_1 \times RV$	2.761,00
10		23.243,00
15		48.402,00
20		80.768,00
Hull		
5	$A_h \times RV_a$	0,00
10		187.740,00
15		0,00
20		238.140,00
Superstructure		
5	$A_s \times C_1 \times RV$	689,00
10		14.533,00
15		31.536,00
20		53.400,00
TOTAL după 20 ani		418.047,52

Tab. 6.9 Cost of anodes replacement

Years	**Installation zinc anodes/anod(eur)**	**Anodes no.**
5	91,20	8
10	100,30	9
15	111,70	9
20	127,20	11

Determining the total cost for replacing the anodes after 20 years = 38.305.6 Euro

Tab. 6.10 Docking cost

Years	**Dry dock time**	**Dry dock cost** (Eur)
5	0	0,00
10	4,13	62.869,00
15	19,70	334.139,58
20	76,62	1.479.356,00
Total	100,45	1.876.364,58

Determining the cost for replacing the steel

In the case of the studied OSV, it was necessary to replace the steel, a necessity which was noticed during the inspection carried out after 20 years. The affected area was the bottom layer, and it was necessary to replace some steel strips measuring 13 m x 3.3 m, respectively 6m x 2.6 m. The steel volume that had to be replaced was 1,2558 m3, with a plate density of 7.85 tonnes/m3, resulting a quantity of 9.85 tonnes to be replaced

Total cost for steel replacement after 20 years = 7.871.60 Euros

Determining the total cost of the vessel

Residual value = Δ × PV =2700 × 641,3 = 1.731.510,0 Euros

Unoptimized fabrication costs for the studied vessel are presented in table 6.11.

It is mentioned that the construction and repair materials and methods used are the classical ones, customary in the naval industry

Tab. 6.11 *Construction, maintenance and repair costs of the studied OSV*

Cost	**Initial**	**Repair cost**	**5 ani**	**10 ani**	**15 ani**	**20 ani**	**Total Cost** Initial Cost +repair cost
(Euro)							
Initial coating tanks	122.998,00	Tank repair	2.761,00	23.243,00	48.402,00	80.768,00	**278.172,00**
Initial coating deck	37.842,00	Deck repair	67.257,00	73.935,00	82.362,00	93.810,00	**355.206,00**
Initial coating hull	96.390,00	Hull repair	0,00	187.740,00	0,00	238.140,00	**522.270,00**
Initial coating superstructure	95.557,00	Superstructure repair	689,00	14.533,00	31.536,00	53.400,00	**195.715,00**
Zinc anode cost	7.013,00	Zinc anode cost	8.117,00	8.927,00	9.941,00	11.321,00	**45.319,00**
Steel cost	5.780.700,00	Steel cost	0,00	0,00	0,00	7.872,00	**5.788.572,00**
Dry dock cost	0,00	Dry dock cost	0,00	62.869,00	334.140,00	1.479.356,00	**1.876.365,00**
INITIAL COST	**6.140.500,00**		**78.824,00**	**371.247,00**	**506.381,00**	**1.964.667,00**	**9.568.000,00**

6.2 Optimizing the maintenance and repair activities to reduce the costs generated by them

6.2.2 Numerical application

In view of determining the optimal cost for maintenance and repairs, a Java program was elaborated, using the Netbeans integrated development environment. The optimization was achieved for the total costs of construction and exploitation (maintenance/repairs) for the entire life duration of a vessel.

The program achieves a cost analysis for the entire life duration of a vessel, with the following results:

- Total optimized cost of the vessel;
- Materials which must be used on varieties and quantities;
- Optimized number of days for docking while using the specified materials;
- Information about the percentage of each cost element in the final cost;
- To calculate the optimal alternative, taking into account the multitude of the parameters involved;

- To offer the possibility of various simulations on the entire life duration of the vessel;
- To offer support in decision making, hull maintenance and repairs in real time.

The calculus program is structured as follows:

- Menu for introducing data
- Data menu
- Results menu

The results are delivered in a file consisting in a complete report containing the data of the analysed vessel, the analysed period, the costs corresponding to each anticorrosive method used and to each period of use, explanations for terms employed and, last but not least, the alternatives which are optimal in terms of analysed costs efficiency for ensuring a high reliability.

The program has the presentation windows below.

Fig. 6.7 About windows

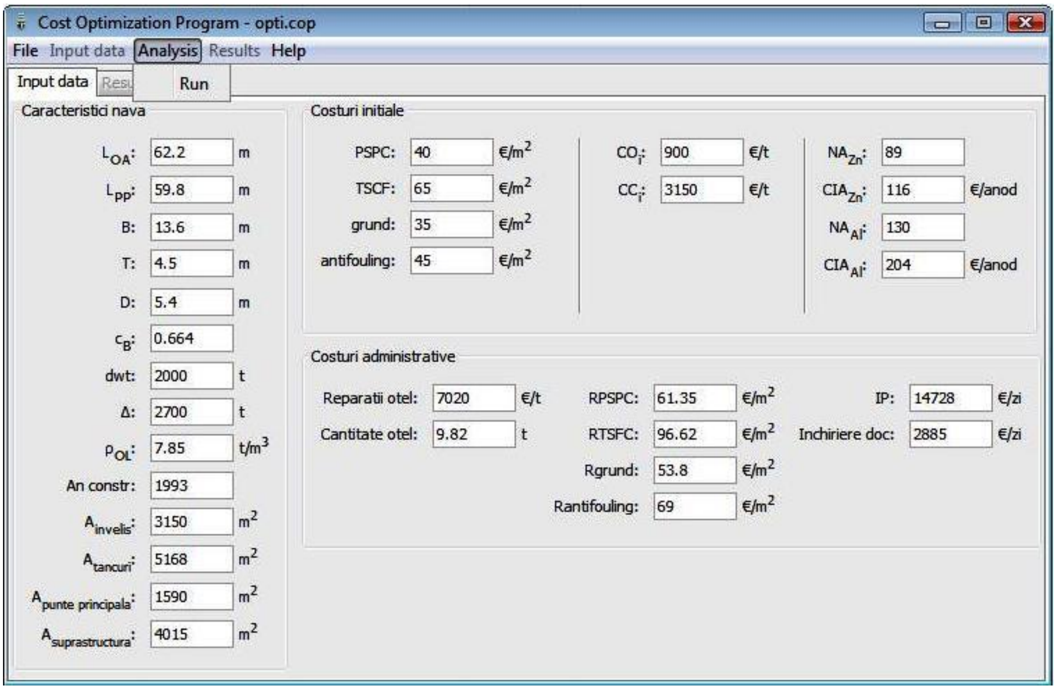

Fig. 6.8 „Analysis” windows

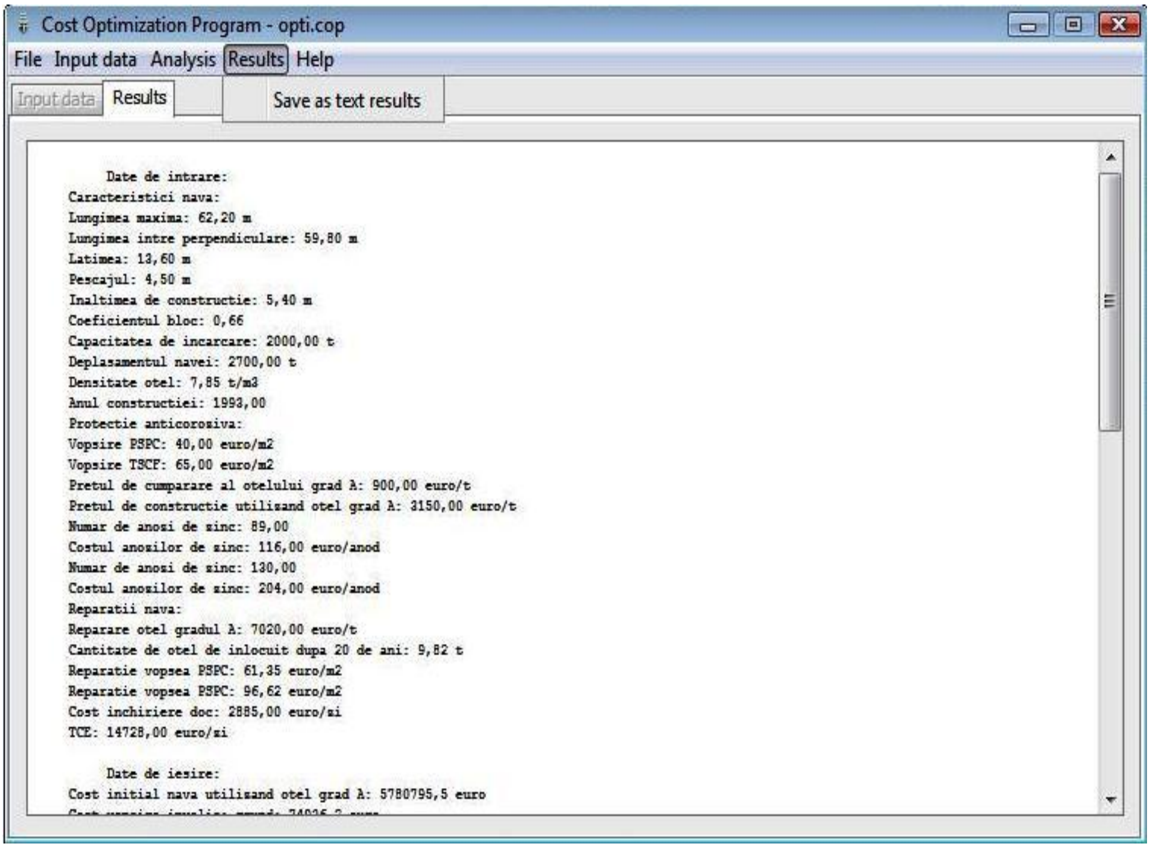

Fig. 6.9 Windows „Results”

Tab. 6.14 *Report generated from the program ”Cost Efficiency Program” for the metal structure of the hull* ***OSV 3300***

Entry data	
Ship characteristics:	
The maximum length	62,20 m
Length between perpendiculars	59,80 m
Width	13,60 m
Draft	4,50 m
Construction height	5,40 m
Block coefficient	0,66
Load capacity	2.000,00 t
Displacement vessel	2.700,00 t
Density steel	7,85 t/m3
Year Built	1993
Corrosion protection:	
PSPC Coating	40,00 euro/m^2
TSCF Coating	65,00 euro/m^2
The purchase price of the grade A steel	900,00 euro/t
The price Construction using grade A steel	3.150,00 euro/t
Number of zinc anodes	89,00
Zinc anodes cost	116,00 euro/anode
Number of aluminium anodes	130,00
Aluminium anodes cost	204,00 euro/anode

Ship repair:	
Grade A steel repair	7.020,00 euro/t
The quantity of steel removed after 20 years	9,82 t
Repair PSPC Coating	61,35 euro/m^2
Repair TSCF Coating	96,62 euro/m^2
Dry dock cost	2.885,00 euro/day
TCE	14.728,00 euro/day

Output data:	**(euro)**			
Initial cost steel vessel using Grade A	5.780.795,50			
Cost antifouling coating	96.346,60			
Cost coating deck: primer	37.825,00			
Cost superstructure coating: primer	95.514,00			
Cost costing tanks: PSPC	140.506,30			
Cost coating tanks: TSCF	228.322,70			
Zinc anodes cost	7.017,20			
Aluminium anodes cost	18.025,50			
	5 ani	**10 ani**	**15 ani**	**20 ani**
	(euro)			
Cost recoating deck	849,60	7.150,70	14.894,20	24.839,60
Cost recoating superstructure	2.145,30	18.056,70	37.610,30	62.723,90
Cost recoating hull - antifouling	2.158,60	18.169,00	37.844,20	63.113,80
Cost recoating tanks PSPC	3.148,80	26.503,80	55.204,70	92.066,60
Cost recoating tanks TSCF	2.975,40	25.044,50	52.165,10	86.997,30
Dry dock cost	0,00	62.901,60	334.056,60	1.479.751,90
Replacement cost zinc anodes	8.114,30	16.228,6	24.342,90	32.457,20
Replacement cost steel	0,00	0,00	0,00	7.847,60

Optimized version for repair work is undertaken to 5 years:		Zinc anodes, hull coated with antifouling paint	
		Ship tanks coated with PSPC	
		The optimum cost of building and repair for 5 years: 6.174.420,90 euros	
Initial investment		Repair and maintenance expenses	
		Duration of use:	5 ani
Coating tanks	140.506,30	Repair tanks	3.148,80
Costing deck	37.825,00	Repair deck	849,60
Coating hull	96.346,60	Repair hull	2.158,60
Coating superstructure	95.514,00	Repair superstructure	2.145,30
Anodes cost	7.017,20	Replacement anodes	0,00
Steel cost	5.780.795,50	Replacement steel	0,00
		Dry dock cost	0,00
Total cost-initial: 6.158.004,40		Total cost - repair:	8302,20

Optimized version for repair work is undertaken to 10 years		Aluminum anodes, hull coated with antifouling paint Ship tanks coated with PSPC **The optimum cost of building and repair for 10 years: 6.301.794,70 euros**		
Initial investment		Repair and maintenance expenses		
		Duration of use:	5 ani	10 ani
Coating tanks	140.506,30	Repair tanks	3.148,80	26.503,80
Costing deck	37.825,00	Repair deck	849,60	7.150,70
Coating hull	96.346,60	Repair hull	2.158,60	18.169,00
Coating superstructure	95.514,00	Repair superstructure	2.145,30	18.056,70
Anodes cost	18.025,50	Replacement anodes	0,00	0,00
Steel cost	5.780.795,50	Replacement steel	0,00	0,00
		Dry dock cost	0,00	62.901,60
Total cost-initial: 6.169.012,70		Total cost - repair	8.302,20	132.782,00

Optimized version for repair work is undertaken to 15 years		Aluminum anodes, hull coated with antifouling paint Ship tanks coated with PSPC **The optimum cost of building and repair for 15 years: 6.648.622,80 euros**			
Initial investment		Repair and maintenance expenses			
		Duration of use:	5 ani	10 ani	15 ani
Coating tanks	140.506,30	Repair tanks	3.148,80	26.503,80	55.204,70
Costing deck	37.825,00	Repair deck	849,60	7.150,70	14.894,20
Coating hull	96.346,60	Repair hull	2.158,60	18.169,00	37.844,20
Coating superstructure	95.514,00	Repair superstructure	2.145,30	18.056,70	37.610,30
Anodes cost	18.025,50	Replacement anodes	0,00	0,00	0,00
Steel cost	5.780.795,50	Replacement steel	0,00	0,00	0,00
		Dry dock cost	0,00	62.901,60	334.056,60
Total cost-initial: 6.169.012,70		Total cost - repair	8.302,20	132.782,00	479.610,00

Optimized version for repair work is undertaken to 20 years		Aluminum anodes, hull coated with antifouling paint Ship tanks coated with PSPC The optimum cost of building and repair for 20 years**: 7.891.508,50 euros**				
Initial investment		Repair and maintenance expenses				
		Duration of use:	5 ani	10 ani	15 ani	20 ani
Coating tanks	140.506,30	Repair tanks	3.148,80	26.503,80	55.204,70	92.066,60
Costing deck	37.825,00	Repair deck	849,60	7.150,70	14.894,20	24.839,60

Coating hull	96.346,60	Repair hull	2.158,60	18.169,00	37.844,20	63.113,80
Coating superstructure	95.514,00	Repair superstructure	2.145,30	18.056,70	37.610,30	62.723,90
Anodes cost	18.025,50	Replacement anodes	0,00	0,00	0,00	0,00
Steel cost	5.780.795,50	Replacement steel	0,00	0,00	0,00	0,00
		Dry dock cost	0,00	62.901,60	334.056,60	1.479.751,90
Total cost-initial: 6.169.012,70		Total cost - repair	8.302,20	132.782,00	479.610,00	1.722.495,80

Chapter 7
General conclusions. Original contributions and perspectives

7.1 General conclusions

In the current international economic context, with shipbuilding having entered a visible regress, the question of efficient goods transportation costs on water is essential. These costs, together with the operational ones, refer to current maintenance and repair costs. Ship owners are thinking about the life extension of the ships they own. Therefore, together with the attention to ship design, and to choosing the on board and deck installations, great attention is given to the phenomenon which produces the greatest wears in ships, namely corrosion.

The subject chosen for this research has been a highly debated one starting with the birth of metallic structure vessels, but it is also a modern preoccupation because the problem of vessel body repair costs has not been completely elucidated yet. Thus, there are still situations when, after a certain amount of time has passed from the beginning of the repair works, the actual costs are much higher than the initially estimated ones and, under these circumstances, ship owners tend to choose to start building new vessels, whose costs are comparable with the repair costs for used ships.

The errors in estimating the costs have negative consequences on carrying out the repair, ship owners forcing the shipyards where the work is carried out to conduct their business at a loss. Therefore, in order to avoid these shortcomings, it is necessary to fully know the degree of ware and the work that has to be carried out, and then to draw up an efficient, budget oriented repairs plan.

A problem which is maybe more important than the repair costs is that of ensuring the classification society requirements from all points of view: local and general resistance, safety in navigation, as well as of ensuring decent living conditions for the on board crew. Satisfying the first two requirements is achieved by calculating the structures and having in view the reduction in plate and frame thickness caused by corrosion.

Corrosion implies numerous aspects, causes and forms of evolution. Fighting the effects of corrosion is also a complex process, with anticorrosive methods specialised on types of corrosion, matching the environment where it evolves. Having in view the fact that this thesis approaches the naval field, corrosion analysis and analysed anticorrosive methods, the latter are adapted to this industry. A particularity of corrosion in the naval field is the large surface exposed to different types of corrosion that unequally affects the body of the vessel.

For this reason, approaching the estimation of the evolution in time of the corrosion rate is currently empirical, generally based on observation, and involves carrying out measurements for various types of structures of various vessels included in a database. In this context, an OSV – whose history of thickness measurements is known – was chosen.

This allowed the achievement of a precise study concentrated on the real evolution of tension in the context of corrosion. The data referring to the vessel analysed gave the information referring to measurements and to the work carried out during periodical inspections of the hull; it gave the possibility to do calculations from an economic standpoint, of maintenance and repair costs corresponding to the entire life duration of the vessel. This information allows efficient costs, which represents a major objective in the shipbuilding industry.

The analysis carried out lead to establishing study methodologies using MEF in view of accurately determining the interest areas on the length of the vessel, which may constitute weak points from the perspective of fogging the board fields.

In conclusion, the costs generated by corrosion cannot be totally reduced, even though the latter does not have an aggressive evolution, and the assumption of significantly reducing the total costs associated with corrosion is valid only through the careful control of the equilibrium between investment, ensured reliability, terms of use, specifics of the vessel, history of same category vessels. Controlling these variables and establishing the optimal combination of factors may ensure an increased efficiency in maintenance and repair costs.

In general terms, for amateurs, owning a vessel is efficient when the construction costs or the acquisition price – to which the maintenance and repair costs are added –, docking taxes, etc. are lower than the income generated.

Cost efficiency is an exercise that a ship owner must permanently perform so that it may govern the associated work culture.

Calculating efficiency in this case implies elaborating viable instruments of planning and analysing performances over time, from an economic and sustainable standpoint, but also identifying the elements that generate the costs for the entire life duration of the vessel.

Other instruments used in this calculation are the identification of possible sources of hidden losses, the potential increase in present and future profit of the vessel, achieving an efficient corrosion management system (from a technical standpoint), effects of corrosion on the vessel structure, and the costs generated for the entire life duration of the vessel.

The main efficiency characteristic is that of promptly and rapidly responding to the events and modifications that may appear during the process of exploiting the vessel. This efficiency process does not only offer flexibility and the capacity to reconfigure, but also autonomy, ensuring a quality level and function ability according to the provisions of the classification society, cost reduction, learning capacity and auto regeneration.

Modern efficiency systems in the naval field were developed based on three essential concepts:

1. sustaining the production of new vessels;
2. maintaining the quality at imposed standards;
3. reducing losses in the vessels exploitation activity.

The current research was based on developing a software program which aims at streamlining the maintenance and repair costs of a vessel from the perspective of corrosion.

The advantages offered by this program are:

-optimizing the docking time;

-the possibility of simulating the materials options in view of lowering the costs and maximizing the period of use;

-reducing the costs of used materials for vessel maintenance and repair;

-a flexible, adaptable and reusable algorithm, to be implemented on any type of vessel.

In view of developing the efficiency system, it was necessary to control and monitor the entire vessel maintenance and repair process, in order to observe which parameters of the process could be improved.

By controlling the process, the standards for repair and maintenance of the vessel are met and improved. The control of a vessel repair and maintenance process is completed when the analysis of the process is achieved from the standpoint of organization, execution, but also of the structural effects resulting from the decisions regarding its execution.

Following study the carried out, it may be observed that the increased percentage in the total cost of construction, maintenance and repairs of the determined acquisition and final phase steel processing costs, respectively 65% of the total cost, is significantly higher than the cost corresponding to auto-corrosive paint, which represents only 15.2%.

From the standpoint of the costs determined by anti-corrosive covering, a significant contribution, of 6% of the total cost, is represented by the hull area, followed by the deck, with 4%, and the tanks, with 3%. An important percentage in the total cost is constituted by the docking cost, representing 19%.

If one is to refer only to maintenance costs for a period of 20 years of functioning, the largest percentage of these costs is represented by docking costs, with a percentage of 62%, followed closely by the painting costs, with a percentage of 36.5%.

Following this analysis, it is observed that in order to streamline the total cost of construction and building this vessel it is necessary to reduce the costs that represent a significant part, respectively the costs corresponding to anti-corrosive covering, and docking costs, by reducing the time necessary for maintenance and repairs, simultaneously with the increase in the vessel's reliability.

The degree to which this is possible constitutes the subject of a detailed study of the technological solutions, as well as of an economic study of the associated costs.

The report generated by the program following the analysis of the entrance data corresponding to the OSV used in this study constitutes the object of this thesis, and determines the costs for each component element: costs for repainting the deck; costs for repainting the supra-structure, layer, tanks; costs for replacing the anodes; docking costs. It takes into consideration possible options for all these elements.

In keeping with the alternatives presented above, concerning the products used both in construction and in anticorrosive protection, a complex strategy for optimizing corrosion costs may be created.

The electronic program responds to a higher complexity, being able to calculate the optimal alternative taking into consideration the multitude of involved parameters and offering the possibility of simulation on the entire life duration of the vessel. Both the optimization process and the simulation process lie at the basis of the program in question. They have different functioning principles, but both bring a considerable contribution in determining the corrosion repair and maintenance costs of the vessel.

Bringing together these two methods was considered necessary because of their specificities. Optimization is a relatively theoretical concept, which makes its practical applications slightly deficient having in view that, during the 20 year period, many different elements interfere and, from the point of view of the ship owner, this constitutes a great advantage in decision making both in the vessel construction phase and during its exploitation.

This program can be used as support in decision making, construction, maintainance and repairs applied in real time to the hull, not only in post facto evaluation.

The multitude of parameters used in calculating the optimal costs and the ease of modifying their values make this program really helpful to the ship owner in streamlining the exploitation costs and in obtaining a superior profit.

For an efficient vessel repairs and maintenance process, it was necessary to cover two stages:

- identifying the influential variables from the standpoint of the costs generated by vessel maintenance and repair;
- real-time processing of the information on the alternatives for materials used and associated costs.

Following the covering of the two stages and the implementation of the development application (in view of streamlining the process), the program shows the optimal maintenance choices, and not only; it calculates the profitability of owning a vessel on the short and long term, displaying the optimum situation of owning a ship for a period of 5 years, 10 years, 15 years and, respectively, 20 years.

For the most common period of owning a ship, respectively 20 years, the optimal choice is represented by painting the entire hull with antifouling paint, through applying aluminium anodes, and by protecting the tanks with PSPC paint.

It may be observed that the zinc anodes are efficient only for a period of 5 years. The initial costs of these anodes is 10,324 Euro, representing 38% of the initial cost of the aluminium anodes, whose replacement, under normal conditions, is not necessary for the entire duration of the vessel's life. At the 10 years landmark, the zinc anodes lose their efficiency, the initial cost of replacing them surpassing that of the aluminium anodes.

- antifouling paint is applied on the hull area located under the floating line of the vessels, its repair being done every 5 years, according to the surface and to the affected area. A high quality of the initial paint may determine a decreased cost of its repairs, but it may vary according to the specificity of the water it navigates in.
- concerning the costs for repainting the tanks, they vary according to the period of use and to the nature of the goods loaded in them. PSPC (Performance standards for layer protection) adopted by the International Maritime Organisation in 2008 set a life expectancy of 15 years, during which the initial covering is expected to be in good shape.

PSPC maintenance and repairs are very important for the covering to remain in good shape for the entire period of 15 years. An alternative to PSPC paint is TSFC paint, to be used for tanks. It guarantees 25 years of use if all the standards concerning the preparation of the substrate and the applying conditions are met. Having in view the experimental state, the high cost of this type of covering may be taken into consideration as an innovative alternative, with a high risk.

The tanks are painted with PSPC based on the efficiency principle, although the TSCF paint reduces the affected surface with 40% and the repairs are carried out once every 10 years. The income obtained by reducing the costs associated to the maintenance and repair of the tanks does not compensate the difference of almost 60% between the initial cost for using PSPC type anti-corrosive protection and the cost for using the TSCF type. After a life duration of 20 years, the total costs for using PSPC paint for the tanks are approximately equal to the initial investment in case of TSCF paint.

A comparison between the vessel under focus in the present study and the alternatives simulated by the calculus "Cost Efficiency Program" can also be carried out.

The total costs generated by corrosion in the case of the studied vessel, after 20 years of use, is 8,883,015 Euro, with primer type paint and zinc anodes being used as anti-corrosive protection on the entire surface of the vessel.

The optimal choice simulated by the program presuppose the use of aluminium anodes, PSPC paint for the tanks, antifouling paint for the hull, and primer paint for the other structural surfaces. Moreover, with this simulated option, it is not necessary to change the steel (which presupposes supplementary costs and a decrease in resistance), as demonstrated in the numerical analysis achieved in 3D-FEM, presented in Chapter 4.

The elements that ensure an increased efficiency in the case of the optimal choice are:

- docking time interpreted as double loss, a first aspect being the dead time of the vessel from a commercial point of view, as well as from the point of view of port docking costs; it is influenced by the duration and frequency of the work carried out on the hull.

- the quality of the materials and procedures used in carrying out maintenance and repair contribute to increasing the functioning duration of the vessel and to reducing the repair and maintenance work, implicitly the cost associated to them. It may be observed that, for a period of 20 years, the use of the formula PSC paint + antifouling + aluminium sacrifice anodes eliminate the necessity of replacing the steel on the hull surface.

- rendering the process efficient may be achieved both from the point of view of the cost associated with the vessel standing time and from that of the actual maintenance and repair costs.

As regards the total cost generated by corrosion on the simulated variant, it amounts to 7,891,509 Euro, approximately 12% lower than the cost of the study vessel. Following the analysis mentioned above, the initial costs of both variants are approximately equal, the difference between the total costs being given by the reduction of maintenance and repair costs.

Taking into consideration the possibility of modifying each of these characteristics, this program may be used in calculating the costs generated by corrosion for the majority of vessel types. It may represent an instrument which is indispensable in making building decisions, and in choosing materials and maintenance and repair works. Estimating the building, maintenance and repair costs, offering a detailed description of the vessel's elements, and approximating the physical effects generated by choosing a particular material lead to making these costs efficient and to maximising the profit.

7.2. Original contributions

The present doctoral thesis is considered to have brought the following original contributions:

- the achievement of a thorough study regarding the present day state of developing systems of maintenance and repair cost efficiency in the shipbuilding industry, and of the impact they have on the economic environment;

- for a clearer image of the negative effects of corrosion, Chapter 3 and Chapter 4 include an analysis of the general and local resistance using 3D-FEM models extended on the entire length of the OSV, leading to obtaining the values of tensions and deformations in the whole vessel structure, including its extremities;

- the achievement of a study on the costs generated by corrosion in the case of the vessel selected, in view of determining the corrosion categories which generate costs, how much they contribute to the final cost, and the methods of reducing these costs without overlooking the quality standards imposed by Classification Societies;

- the achievement of a software system for rendering maintenance and repair costs efficient for the life duration of the vessel; the software was conceived in the Java programming language, using the Netbeans integrated development medium to generate, compile and test the source code.

- the possibility of simulation throughout the life duration of the vessel, as support in making building, maintenance and repair decisions in real-time;

- the electronic processing of experimental data through simulating the combination of factors which make up the total cost, for determining the optimal variant, for which efficiency is maximum, and the criteria had in view by ship owners and classification societies are simultaneously satisfied.

7.3. Dissemination of results

The research carried out on the project entitled “Doctoral scholarships for durable development POSDRU/107/1.5/S/76945” have taken material shape in writing and publishing 5 scientific articles as first author, both in specialised journals and in international scientific conference volumes, as follows:

- articles published in ISI Web of Science conference volumes – 2
- articles published in international scientific conference volumes indexed in IDB – 2
- articles published in specialised bulletins and journals – 1

Two of the 4 articles published in conference volumes were presented during the respective scientific events.

The dissemination of results was also achieved by participating in scientific sessions organised on the POSDRU project.

7.4 Future directions for extending the research

The research carried out so far will be continued through:

- developing new algorithms for cost efficiency;

-developing new directions for research on total cost optimization for building and exploitation for the entire life duration of a vessel, namely supplementary development of aspects related to the influence on the evolution of corrosion depending on vessel type, water salinity, etc.

- raising the complexity of the optimal variant analysis through introducing elements pertaining to the navigation area for the vessel studied, docking variants, docking costs (in keeping with the navigation area), painting variants (automatic or non-automatic), etc.

- implementing the *Cost Efficiency Program* software for all types of vessels.

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safety coefficients

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