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Procedure for Measuring Shipbuilding Process Optimisation Results after using Modular Outfitting Concept

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On its way to becoming successful and competitive on the world shipbuilding market, the shipyard has to build quality, have small cost of production process and short delivery time of the ship. Optimisation of the shipbuilding process using a modular outfitting concept needs some changes in design and technological processes in shipbuilding. It needs some changes in outfitting by redirectioning of some outfitting works from blocks, berth and outfitting after launching of the ship towards the workshop. This is a way to shorten the time of the shipbuilding process, reduce costs, increase of competitiveness, without investment in new facilities, machines and tools. In this paper, a model which shows interdependence between various activities in the shipbuilding process is described. This is a vehicle which can be used for research on the dependence of the shipbuilding process in relation to some changes in the outfitting process while shifting some outfitting work from on-board towards outfitting workshops. Those workshops can be either a part of the shipyard or a part of outsourcing. On the basis of the results obtained by this research, it is possible to measure optimisation results as a consequence of using a new modular outfitting concept within the shipbuilding process. In this way, a higher process efficiency, reduced activity cost and durations within the shipbuilding process can be achieved. The authors suggest that further improvement is possible by introducing higher degree of standardisation, unification and typification of ship systems and structures, particularly adapted to a modular outfitting concept, and additionally increased by way of on-block outfits.

Postupak mjerenja rezultata optimizacije brodograđevnog procesa nakon primjene koncepta modularnog opremanja

Izvornoznanstveni članak

Ako brodogradilište želi biti uspješno i konkurentno na svjetskom brodograđevnom tržištu, mora graditi kvalitetno, imati niske proizvodne troškove i kratke rokove isporuke. Optimizacija procesa gradnje i opremanja broda primjenom koncepcije modularnog opremanja broda uvodi promjene u projektnom i tehnološkom procesu gradnje brodova, preusmjeravanjem dijela radova opremanja u sekcije, na navozu i završnog opremanja nakon porinuća broda u radionice opremanja. Time se skraćuje trajanje gradnje i opremanja broda, smanjuju troškovi i povećava konkurentnost brodogradilišta, a da za to nije potrebno investirati dodatna financijska sredstva. Izradom modela međusobno zavisnih aktivnosti proizvodnog procesa gradnje i opremanja broda, dobiven je alat za istraživanje međuzavisnosti odnosa gradnje i opremanja broda, analizirajući odziv sistema na pobudu nastalu izmjenom uvjeta i načina gradnje i opremanja broda uvjetovanih preusmjeravanjem određenih radova opremanja iz faze opremanja na navozu i nakon porinuća broda, u fazu modularnog opremanja u radionice opremanja. Radionica modularnog opremanja može biti dio brodogradilišta ili u outsourcingu. Tijekom istraživanja osnovana je procedura za mjerenje rezultata optimizacije brodograđevnog procesa nakon primjene novog modularnog koncepta opremanja. Time je moguće u ranoj fazi gradnje broda predvidjeti koncepciju gradnje i opremanja broda, koja osigurava veću učinkovitost uz manje troškove i trajanje gradnje i opremanja broda. Istim alatom i tehnikom moguće je već u fazi ugovaranja broda precizirati troškove, potrebne resurse i vrijeme trajanja procesa gradnje i opremanja broda. Autori sugeriraju daljnje unaprjeđenje koncepcije modularnog opremanja standardizacijom, unifikacijom i tipizacijom brodskih sistema i strukture prilagođenih izradi velikih blokova opreme.

Key words:
Modular outfitting
On-block outfit
Optimisation
Shipbuilding
Ship systems

Ključne riječi:
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Symbols/Oznake

t (i, j)	- duration of activity i-j, s - trajanje aktivnosti i-j	*TE* (j)	- earliest activity i-j finish time, s - najraniji završetak aktivnosti i-j
TE (i)	- earliest activity i-j start time, s - najraniji početak aktivnosti i-j	*TL* (j)	- latest activity i-j finish time, s - najkasniji završetak aktivnosti i-j
TL (i)	- latest activity i-j start time, s - najkasniji početak aktivnosti i-j		

1. Introduction

In this paper, research of an existing ship assembly and outfitting production process in one shipyard is presented. The main goal of this research was to develop a procedure for measuring optimisation results after introducing a modular outfitting concept within the observed present shipbuilding process. The observed shipyard spends a considerable part of time in outfitting on the berth and outfitting after launching. The outfitting on block is satisfactory in relation to shape of blocks and transportation vehicles. Increase of the on-block outfitting level can be realised by producing large blocks whose shape and size allow for a higher level of outfitting [1]. This approach requires additional investment in the transport vehicles capacities and suitable platforms for on-block outfitting, but that is not included within this research. In this paper, optimisation of a shipbuilding process, which does not require any investment to improve outfitting was analysed. Optimisation is based on shifting of the parts of outfitting work from berth and final outfitting after launching, towards outfitting workshops, where outfit assembly, on-unit outfit and on-block outfit are used. This optimisation is performed independently of hull production and can be performed before hull assemblies are ready to be moved on berth for erection.

Research contributes to a decrease in activity durations and cost reductions in the shipbuilding process. Results are obtained by the following methodology: *optimisation* [2], *branch-and-bound method* [3], *data collecting method* [4] and *fuzzy scheduling technique* [5].

2. Outline of shipbuilding and outfitting production process

The typical example of a network model [6] of a shipbuilding production process in observed shipyard is shown in Figure 1. Generally, it consists of five independent branches which are performed in parallel, but with some phase shifts. The first branch represents the hull structure production [7]. Other branches represent outfitting processes that are sorted into four branches: on-block outfitting, modular outfitting, on-board outfitting and final outfitting after launching. As shown on network model in Figure 1, the longest branch represents the basic shipbuilding process. Other outfitting processes are included in later phases, when structure blocks are ready to be outfitted [8]. The duration of the shipbuilding process can be reduced in two ways; by reducing the time of hull production, or by reducing the time of outfitting on board [9]. As the observed shipyard installed a new facility for pre-processing of steel plates and profiles, micro panel line and panel line, improvement in this segment of production was not further analysed [10]. There are also some elements in the process of on-block outfitting, which could improve outfitting process, but as mentioned previously, it was also not a topic of this research.

In this paper, research is oriented toward duration reductions of the on-board outfitting process and final outfitting after launching. In this segment of the shipbuilding process, the observed shipyard has potential and possibility to improve the outfitting process and decrease production costs, without any investments in improvement of facilities, machines and tools [11].

3. Procedure for measuring optimisation results

Optimisation of the existing shipbuilding process in the observed shipyard is carried out on the basis of activity durations, as shown in Table 1. The input data are collected by using *the data collection method* from the building of chemical and oil product tanker of 47 300 tdw. Activity duration expressed in working hours is suitable for measuring efficiency of the production process and is a convenient approach to show cost and outfitting duration, when the working hours are multiplied by price of work or divided by number of workers [12]. It is a successful tool for calculation and planning in the earlier stage of the shipbuilding process [13].

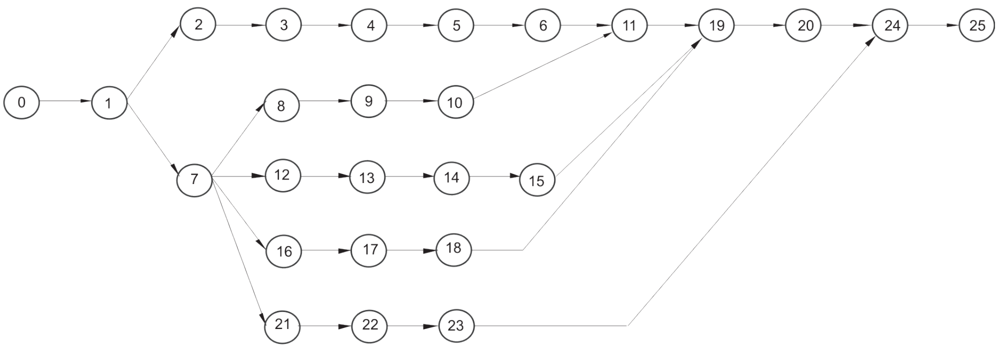

Figure 1. Network model of shipbuilding and outfitting process

Slika 1. Mrežni dijagram proizvodnog procesa gradnje i opremanja broda

Optimisation of the outfitting process is oriented towards increasing the portion of modular outfitting. In that case, a part of outfitting which in the present process participates with 43% and in final outfitting with 26%, will be performed in an outfitting workshop, whose participation in overall outfitting is only 5% nowadays. Generally, on-unit and on-block outfits are installed on board directly after the hull section is erected on berth, with the intention of easing painting of ship sections and preventing damage of equipment.

The concept of modular outfitting is based on manufacturing outfit assemblies, on-unit and on-block outfits [14].

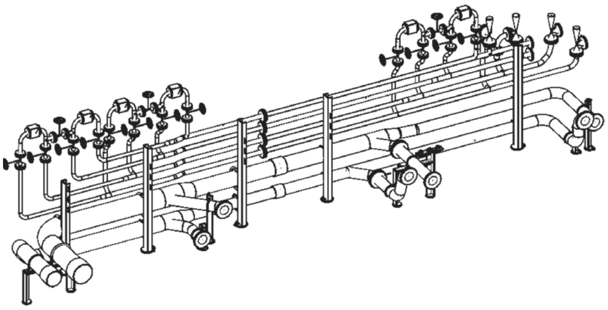

Figure 2. Outfit assembly

Slika 2. Sklop opreme

Outfit assembly represents the simplest level of outfitting in a workshop [15]. It consists of steel elements such as pipes, pipe supports, valves, filters, steel plates and profiles, etc. (Figure 2). On-unit outfits are a higher level of outfitting, which include some part of assembly outfit with pumps or other equipment (Figure 3). On-block outfits are the highest level of outfitting which includes outfit assembly and on-unit outfit, assembled together with equipment for crew passages (floors, railing, handrail, stairs and ladders), ventilation ducts, and cable traces (Figure 4). Outfit assembly, on-unit and on-block outfits are produced in workshop which can be a part of shipyard or in outsourcing. Testing and quality controls are performed also in the workshop, which lead to minimization of work performed on board [16].

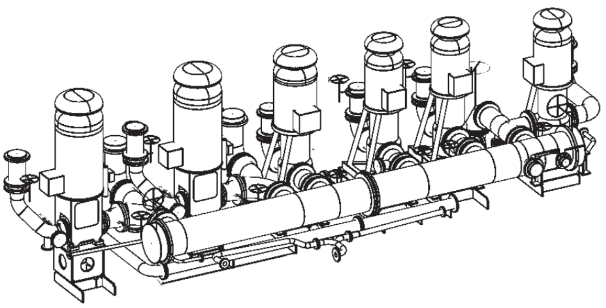

Figure 3. On-unit outfit

Slika 3. Modul opreme

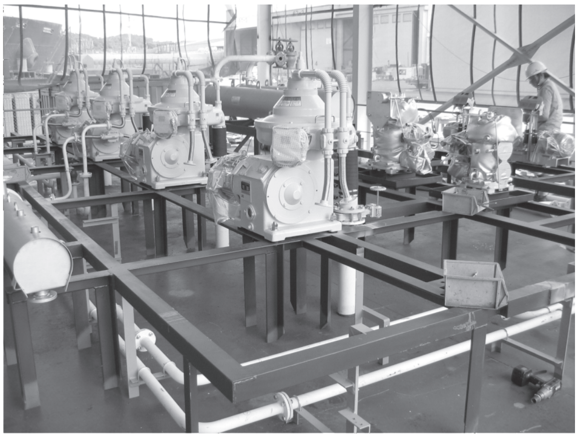

Figure 4. On-block outfit for separator room assembled in workshop

Slika 4. Blok opreme prostorije separatora u opremanju u radionici

The use of the modular concept of outfitting reduce the time spent on ship outfitting but require more time and investment during ship design, construction and preparation of the production process. [17] That is a consequence of adapting the ship design to the concept of modular outfitting, a necessity of higher quality of documentation and transporting of outfit assemblies, on-unit and on-block outfits on-board [18]. Amount of working hours in workshop is increased, because some work from on-board is relocated to the workshop and required level of the quality and precision has to be upgraded [19].

In this paper, the impact of increasing the portion of modular outfitting in relation to decreasing cost of on-board and final outfitting is analysed, as well as increasing cost for designing, constructing and preparing production process for higher level of modular outfitting and higher level of accuracy during manufacturing [20]. For this purpose, the new algorithm for analysis and validation of the above mentioned relations is developed. The calculation is based on assumption obtained by the empirical method and observations of a past similar process by using data collecting method.

Table 1. Duration of shipbuilding and outfitting production activities on tanker for chemicals and oil products of 47 300 tdw

Tablica 1. Trajanje aktivnosti procesa gradnje i opremanja tankera za kemikalije i naftne prerađevine nosivosti 47 300 t

Activity / Aktivnost		Activity description / Opis aktivnosti	Duration (working hours) / Trajanje (radni sati)
i	j		
0	1	Contracting / Ugovaranje	3 000
1	7	Systems design / Projektiranje sistema	50 000
1	2	Hull design / Projektiranje strukture	20 000
7	12	Workshop drawings for modular outfitting / Konsttruiranje sistema za modularno opremanje	10 000
12	13	Production preparation for modular outfitting	2 000
9	10	Elements manufacturing elements for on-block outfitting / Izrada detalja brodske opreme za opremanje u sekcije	30 000
13	14	Elements manufacturing elements for modular outfitting / Izrada detalja brodske opreme za modularno opremanje	10 000
17	18	Elements manufacturing elements for on-board outfitting / Izrada detalja brodske opreme za opremanje na navozu	90 000
22	23	Elements manufacturing elements for final outfitting / Izrada detalja brodske opreme za završno opremanje	30 000
2	3	Workshop drawings for hull structure / Konstruiranje strukture	15 000
3	4	Preparation of hull structure production / Priprema proizvodnog procesa izrade sekcija	5 000
4	5	Manufacturing of hull structure elements / Izrada detalja strukture	50 000
5	6	Hull structure pre-assembly / Izrada sklopova sekcija (mala predmontaža)	80 000
6	11	Hull structure assembly / Predmontaža sekcija brodskog trupa	115 000
10	11	On-block outfitting / Opremanje sekcija	150 000
11	19	Hull structure erection / Montaža sekcija na navoz	300 000
14	15	Modular outfitting / Modularno opremanje broda	30 000
15	19	Outfitting assemblies, modules and blocks transportation on board / Transport sklopova, modula i blokova opreme na brod	2 000
18	19	Equipment Transportation for on-board outfitting / Transport detalja brodske opreme za montažu na navoz	5 000
19	20	On-board outfitting / Opremanje na navozu	250 000
20	24	Launching / Porinuće	2 000
24	25	Final outfitting after launching / Završno opremanje u opremnoj luci	150 000
23	24	Transportation of equipment for final outfitting / Transport detalja brodske opreme za završno opremanje	1 000
7	8	Workshop drawings for on-block outfitting / Konstruiranje sistema za opremanje sekcija	20 000
7	16	Workshop drawings for on-board outfitting / Konstruiranje sistema za montažu na navozu	50 000
7	21	Workshop drawings for final outfitting / Konstruiranje sistema za završno opremanje	20 000
8	9	Production preparation of on-block outfitting / Priprema proizvodnog procesa za opremanje sekcija	5 000
16	17	Production preparation of on-board outfitting / Priprema proizvodnog procesa za montažu na navozu	12 500
21	22	Production preparation of final outfitting / Priprema proizvodnog procesa za završno opremanje	5 000
		Total / Ukupno	**1 512 500**

The long term statistics in observed shipyard show that the cost of work performed in the workshop compared with the same work performed on section, on-board or in final outfitting is related as 1 : 3 : 5 : 7. It means that the work can be made in the workshop, but instead is performed on final outfitting, costs can be up to seven times multiplied.

This is a basic statement for a derived algorithm and states that the job with *x* working hours, which is relocated from section to workshop, is *x/3* cheaper, also shifting job from on-board to workshop is *x/5* cheaper, and shifting a job from final outfitting to workshop consists of *x/7* of preceding working hours.

new values of activity duration are distributed according to the following equation:

$$D2 = 30\,000 + 0/3 + 90\,000/5 + 0/7 = 48\,000, \tag{5}$$

$$D3 = 250\,000 - 90\,000 = 160\,000. \tag{6}$$

By increasing the portion of activity duration in modular outfitting, the costs for designing, constructing and preparation of the shipbuilding process are decreased. Also, the manufacturing and transport costs during modular outfitting are increased, while manufacturing, transport and outfitting costs for the other three phases are decreased. This calculation and obtained values are presented in Table 3.

Table 2. Comparison of activity duration against present and modular ship outfitting concepts

Tablica 2. Usporedba trajanja aktivnosti prema postojećem i modularnom konceptu opremanja broda

		A	**B**	**C**	**D**	**E**
	Activity description / Opis aktivnosti	**Present activity duration (working hours) / Trajanje faza opremanja (radni sati)**	**Present activity duration (%) / Udio faza opremanja (%)**	**Diference in activity duration (working hours) / Radni sati unaprjeđenja modularnim opremanem (radni sati)**	**New concept activity duration (working hours) / Novo trajanje faza opremanja (radni sati)**	**Relative reduction of activity duration (%) / Relativno smanjenje radova opremanja (%)**
1.	On-block outfitting / Opremanje sekcija	150 000	25,86	0	150 000	0,00
2.	Modular outfitting / Modularno opremanje	30 000	5,17	+ 18 000	48 000	+ 60,00
3.	On-board outfitting / Opremanje na navozu	250 000	43,10	- 90 000	160 000	- 36,00
4.	Final outfitting / Završno opremanje	150 000	25,86	0	150 000	0,00

The values presented in Table 2 are derived from the following equations:

$$D1 = A1 - C, \tag{1}$$

$$D2 = A2 + C2/3 + C3/5 + C4/7, \tag{2}$$

$$D3 = A3 - C3, \tag{3}$$

$$D4 = A4 - C4, \tag{4}$$

where letters represent columns and numbers represent rows. Increase of activity duration by improving modular outfitting is calculated from equation (2). New values for activity duration on-section, on-board and final outfitting are obtained from equations (1), (3) and (4).

Example: By application of modular outfitting in workshop, a quantity of 90,000 working hours is shifted from on-board outfitting to outfitting in the workshop and

Correction coefficient (column A) defines impact on change of activity duration for observed process caused by redirection of some outfitting process. For example, if some activity of on-board outfitting decreases by 10%, it does not mean that design or construction costs will be decreased by the same percentage. In the process of correction coefficient determination, the fuzzy scheduling technique appeared as appropriate technique to be used. According to this technique, assessment of impact in some events which happened in surrounding process, is made by experience and conclusions based on past events. This approach produces some errors in calculation, particularly in processes which include more human activities. Therefore, duration of the processes can strongly depend upon a skill or motivation of workers [21]. The correction coefficient value is between 0 and 1. Value 0 represents a case when some changes in surrounding process do not have an impact on observed process, while value 1 represents maximal impact on observed processes. The correction coefficient value is determined empirically. Calculations of some process duration are based on connections between activities in the network model of shipbuilding and outfitting process (Figure 1). As far as some activities are mutually linked and have time overlap (Figure 5), the completion of observed activity does not have a direct influence on the beginning of the following activity. The following activity can start immediately after the minimum conditions are satisfied. For this reason, the overlap factor is introduced in network model calculation.

The activity overlap indicator is determined according to a general plan of the shipbuilding process which includes their key data and available resources for realisation of observed activity. The activity overlap indicator is calculated in Table 4.

The time dependence between activities in shipbuilding process and outfitting is shown in Table 5. This calculation is based on duration of observed activity, until the next activity is started. Calculations of processes duration between activities in network model of shipbuilding and outfitting is performed according to following equations:

$$TE(j) = max\ \{TE(i) + t(i, j)\}, \tag{7}$$

$$TL(i) = min\ \{TL(j) - t(i, j)\}. \tag{8}$$

Table 3. Calculation of costs distribution by using modular outfitting concept

Tablica 3. Izračun raspodjele troškova primjenom koncepta modularnog opremanja broda

			A	***B***	***C***	***D***
	i	**j**	**Correction coefficent / Koeficijent nelinearnosti**	**Present activity duration / Radni sati opremanja - konvencionalno**	**New concept activity duration / Radni sati opremanja- unaprjeđenje**	**Equation for calculating column *C* / Izraz za računanje kolone *C***
1.	0	1	0,0	3 000	3 000	*C*1=*B*1+*A*1*(“Table 2”(*E*5)**B*1)/100
2.	1	7	0,2	50 000	53 600	*C*2=*B*2+*A*2*(“Table 2”(*E*5)**B*2)/100
3.	1	2	0,1	20 000	20 720	*C*3=*B*3+*A*3*(“Table 2”(*E*5)**B*3)/100
4.	7	12	0,4	10 000	11 440	*C*4=*B*4+*A*4*(“Table 2”(*E*5)**B*4)/100
5.	12	13	0,4	2 000	2 288	*C*5=*B*5+*A*5*(“Table 2”(*E*5)**B*5)/100
6.	9	10	1,0	30 000	30 000	*C*6=*B*6-*A*6*(“Table 2”(*E*1)**B*6)/(100*3)
7.	13	14	1,0	10 000	16 480	*C*7=*B*7+(*B*6-*C*6)+(*B*8-*C*8)+(*B*9-*C*9)
8.	17	18	1,0	90 000	83 520	*C*8=*B*8-*A*8*(“Table 2”(*E*3)**B*8)/(100*5)
9.	22	23	1,0	30 000	30 000	*C*9=*B*9-*A*9*(“Table 2”(*E*4)**B*9)/(100*7)
10.	2	3	0,2	15 000	16 080	*C*10=*B*10+*A*10*(“Table 2”(*E*5)**B*10)/100
11.	3	4	0,0	5 000	5 000	*C*11=*B*11+*A*11*(“Table 2”(*E*5)**B*11)/100
12.	4	5	0,0	50 000	50 000	*C*12=*B*12+*A*12*(“Table 2”(*E*5)**B*12)/100
13.	5	6	0,0	80 000	80 000	*C*13=*B*13+*A*13*(“Table 2”(*E*5)**B*13)/100
14.	6	11	0,0	115 000	115 000	*C*14=*B*14+*A*14*(“Table 2”(*E*5)**B*14)/100
15.	10	11	1,0	150 000	150 000	*C*15=”Table 2”(*D*1)
16.	11	19	0,0	300 000	300 000	*C*16=*B*16+*A*16*(“Table 2”(*E*5)**B*16)/100
17.	14	15	1,0	30 000	48 000	*C*17=”Table 2”(*D*2)
18.	15	19	1,0	2 000	2 720	*C*18=*B*18+*A*18*(“Table 2”(*E*5)**B*18)/100
19.	18	19	1,0	5 000	3 200	*C*19=*B*19-*A*19*(“Table 2”(*E*3)**B*19)/100
20.	19	20	1,0	250 000	160 000	*C*20=”Table 2”(*D*3)
21.	20	24	0,0	2 000	2 000	*C*21=*B*21+*A*21*(“Table 2”(*E*5)**B*21)/100
22.	24	25	1,0	150 000	150 000	*C*22=”Table 2”(*D*4)
23.	23	24	0,7	1 000	1 000	*C*23=*B*23-*A*23*(“Table 2”(*E*4)**B*23)/100
24.	7	8	0,2	20 000	20 000	*C*24=*B*24-*A*24*(“Table 2”(*E*1)**B*24)/100
25.	7	16	0,4	50 000	42 800	*C*25=*B*25-*A*25*(“Table 2”(*E*3)**B*25)/100
26.	7	21	0,4	20 000	20 000	*C*26=*B*26-*A*26*(“Table 2”(*E*4)**B*26)/100
27.	8	9	0,2	5 000	5 000	*C*27=*B*27-*A*27*(“Table 2”(*E*1)**B*27)/100
28.	16	17	0,4	12 500	10 700	*C*28=*B*28-*A*28*(“Table 2”(*E*3)**B*28)/100
29.	21	22	0,4	5 000	5 000	*C*29=*B*29-*A*29*(“Table 2”(*E*4)**B*29)/100
			TOTAL / UKUPNO	**1 512 500**	**1 437 548**	

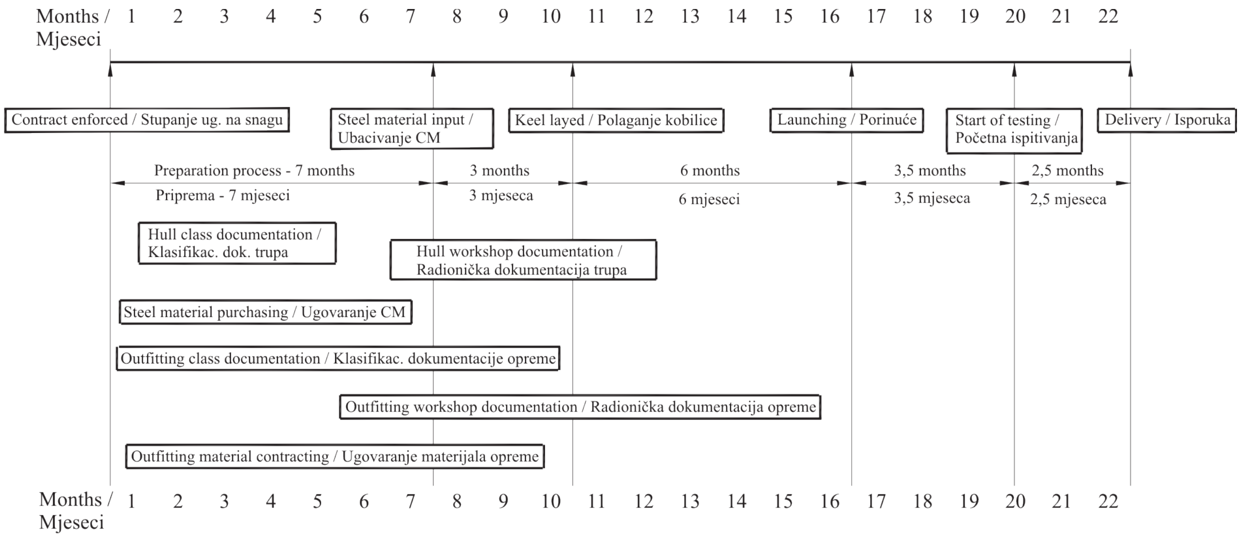

Figure 5. The base planner of shipbuilding process oriented towards preparation phase of shipbuilding process

Slika 5. Osnovni rokovnik gradnje broda usmjeren na pripremnu fazu procesa gradnje broda

Table 4. Calculating of activity overlap indicator

Tablica 4. Proračun indikatora preklapanja aktivnosti

			A	*B*	*C*	*D*
	i	j	**Activity overlap (%) / Preklapanje procesa (%)**	**Activity overlap indicator / Faktor preklapanja procesa**	**Overlap-free activity duration (working hours) / Trajanje procesa bez preklapanja (radni sati)**	**Equation for calculating value in column C / Izraz za računanje kolone C**
1.	0	1	20	0,80	2 400	*C*1=((100-*A*1)/100)*("Tabl"3(*C*1))
2.	1	7	50	0,50	26 800	*C*2=((100-*A*1)/100)*("Tabl"3(*C*2))
3.	1	2	30	0,70	14 504	*C*3=((100-*A*3)/100)*("Tabl"3(*C*3))
4.	7	12	40	0,60	6 864	*C*4=((100-*A*4)/100)*("Tabl"3(*C*4))
5.	12	13	50	0,50	1 144	*C*5=((100-*A*5)/100)*("Tabl"3(*C*5))
6.	9	10	40	0,60	18 000	*C*6=((100-*A*6)/100)*("Tabl"3(*C*6))
7.	13	14	30	0,70	11 536	*C*7=((100-*A*7)/100)*("Tabl"3(*C*7))
8.	17	18	40	0,60	50 112	*C*8=((100-*A*8)/100)*("Tabl"3(*C*8))
9.	22	23	40	0,60	18 000	*C*9=((100-*A*9)/100)*("Tabl"3(*C*9))
10.	2	3	40	0,60	9 648	*C*10=((100-*A*10)/100)*("Tabl"3(*C*10))
11.	3	4	50	0,50	2 500	*C*11=((100-*A*11)/100)*("Tabl"3(*C*11))
12.	4	5	50	0,50	25 000	*C*12=((100-*A*12)/100)*("Tabl"3(*C*12))
13.	5	6	50	0,50	40 000	*C*13=((100-*A*13)/100)*("Tabl"3(*C*13))
14.	6	11	50	0,50	57 500	*C*14=((100-*A*14)/100)*("Tabl"3(*C*14))
15.	10	11	40	0,60	90 000	*C*15=((100-*A*15)/100)*("Tabl"3(*C*15))
16.	11	19	55	0,45	135 000	*C*16=((100-*A*16)/100)*("Tabl"3(*C*16))
17.	14	15	30	0,70	33 600	*C*17=((100-*A*17)/100)*("Tabl"3(*C*17))
18.	15	19	30	0,70	1 904	*C*18=((100-*A*18)/100)*("Tabl"3(*C*18))
19.	18	19	30	0,70	2 240	*C*19=((100-*A*19)/100)*("Tabl"3(*C*19))
20.	19	20	45	0,55	88 000	*C*20=((100-*A*20)/100)*("Tabl"3(*C*20))
21.	20	24	0	1,00	2 000	*C*21=((100-*A*21)/100)*("Tabl"3(*C*21))
22.	24	25	20	0,80	120 000	*C*22=((100-*A*22)/100)*("Tabl"3(*C*22))
23.	23	24	20	0,80	800	*C*23=((100-*A*23)/100)*("Tabl"3(*C*23))
24.	7	8	40	0,60	12 000	*C*24=((100-*A*24)/100)*("Tabl"3(*C*24))
25.	7	16	40	0,60	25 680	*C*25=((100-*A*25)/100)*("Tabl"3(*C*25))
26.	7	21	0	1,00	20 000	*C*26=((100-*A*26)/100)*("Tabl"3(*C*26))
27.	8	9	50	0,50	2 500	*C*27=((100-*A*27)/100)*("Tabl"3(*C*27))
28.	16	17	50	0,50	5 350	*C*28=((100-*A*28)/100)*("Tabl"3(*C*28))
29.	21	22	40	0,60	3 000	*C*29=((100-*A*29)/100)*("Tabl"3(*C*29))
				TOTAL / UKUPNO	**826 082**	

According to expressions (7) and (8), the earliest and latest activity start and finish times are calculated for each activity (Table 5). These results define the time reserve for activating the next activity. The activities which do not have a time reserve, in accordance with the following equations:

$$TE(i) = TL(i), \tag{9}$$

$$TE(j) = TL(j), \tag{10}$$

are on outfitting critical path. In the presented example, the process on the critical path is hull structure production, on-board and final outfitting on the following path: 0-1-5-2-3-4-5-6-11-19-20-24-25. Total duration of shipbuilding process is defined with the finish of the last activity from network model, or when activities 24 - 25 are accomplished with total duration of shipbuilding process:

$$TE(25) = TL(25) = 496\ 552. \tag{11}$$

For the observed example, the shipbuilding process is finished after 496,552 hours. This approach enables planning and cost calculation in the earliest stage of shipbuilding process. If each activity duration and deadlines are assigned, it is possible to determine the number of workers and quantity of resources which are needed to finish the activity on time. For example, for accomplishment activity 1-7 (system design) up to the start of next activity, 26,800 working hours are needed. If these working hours are divided by monthly working hours per person, it follows that this activity can be completed within 149 person months. Furthermore, if the labour cost is multiplied by the working hours, it is possible to calculate the cost of each activity [8].

Table 5. Calculation of earliest and latest activity start and finish times in network model depicted in Figure 1.

Tablica 5. Izračun najranijeg i najkasnijeg početka i završetka aktivnosti prema mrežnom dijagramu na Slici 1.

	i	j	*A*	*B*	*C*	*D*	*E*
			TE(i)	**TL(j)**	**TE(j)**	**TL(i)**	**t(i, j)**
1.	0	1	0	2 400	2 400	0	2 400
2.	1	7	2 400	29 052	29 200	2 252	26 800
3.	1	2	2 400	16 904	16 904	2 400	14 504
4.	7	12	29 200	238 368	36 064	231 504	6 864
5.	12	13	36 064	239 512	37 208	238 368	1 144
6.	9	10	41 200	61 552	59 200	43 552	18 000
7.	13	14	36 064	251 048	47 600	239 512	11 536
8.	17	18	60 230	284 312	110 342	234 200	50 112
9.	22	23	52 200	375 752	70 200	357 752	18 000
10.	2	3	16 904	26 552	26 552	16 904	9 648
11.	3	4	26 552	29 052	29 052	26 552	2 500
12.	4	5	29 052	54 052	54 052	29 052	25 000
13.	5	6	54 052	94 052	94 052	54 052	40 000
14.	6	11	94 052	151 552	151 552	94 052	57 500
15.	10	11	59 200	151 552	149 200	61 552	90 000
16.	11	19	151 552	286 552	286 552	151 552	135 000
17.	14	15	47 600	284 648	81 200	251 048	33 600
18.	15	19	81 200	286 552	83 104	284 648	1 904
19.	18	19	110 342	286 552	112 582	284 312	2 240
20.	19	20	286 552	374 552	374 552	286 552	88 000
21.	20	24	374 552	376 552	376 552	374 552	2 000
22.	24	25	376 552	496 552	496 552	376 552	120 000
23.	23	24	70 200	376 552	71 000	375 752	800
24.	7	8	29 200	41 052	41 200	29 052	12 000
25.	7	16	29 200	228 850	54 880	203 170	25 680
26.	7	21	29 200	354 752	49 200	334 752	20 000
27.	8	9	41 200	43 552	43 700	41 052	2 500
28.	16	17	54 880	234 200	60 230	228 850	5 350
29.	21	22	49 200	357 752	52 200	354 752	3 000

4. Research results

A simulation, based on algorithm described in this paper, is performed on four feasible network model layouts.

It is taken into consideration that it is not possible to eliminate absolutely on-board and final outfitting, and that present on-block outfitting satisfies the required level of outfitting. In that case, further reduction of shipbuilding process duration can be realised by improving, the on-board and final outfitting process.

Results obtained by simulation are presented in Table 6.

The initial level of outfitting in observed shipyard is shown in the first row in Table 6.

In a simulation of the case 190,000 working hours are shifted from on-board outfitting to modular outfitting. In the case 2,170,000 working hours are shifted from on-board outfitting to modular outfitting. Case 3 shows combination of shifting 90,000 working hours from on-board outfitting and 50,000 working hours from final outfitting to modular outfitting. The final and optimal case includes shifting of 170,000 working hours from on-board outfitting and 100,000 working hours from final outfitting to modular outfitting. The last case assumes that the maximum level of improving modular outfitting in workshop is achieved.

The authors suggest that modular outfitting should be more implemented towards building of standard grand block outfits.

This approach enable wider implementation of workshop outfitting instead of on-board and final outfitting, especially in the separator room, engine control room, boiler room and hydraulic room.

Further research will be focused on standardisation, unification and typification of ship systems which should be more adaptable towards a modular outfitting concept. Namely, by analysing several types of merchant ships for various purposes, with various velocities and engine power, it is possible to obtain a set of characteristics of general ship systems. Those characteristics can be classified according to deadweight, length, engine power and velocity, and such information gives possibilities to obtain new standards in project and design that enable implementation of modular outfitting concept on grand block outfits.

5. Conclusion

The described modular outfitting concept used for optimisation of the observed shipbuilding process can be applicable to any shipyard regardless of type, purpose, size, deadweight, and velocity of ship produced. Authors have proposed the procedure for measuring results of introduced optimisation within the shipbuilding process. They suggest that shipyards have to have an adequate data collecting method, so as to measure parameters of process response caused by impulses occurring from surrounding activities. Such parameters are then used to calculate established coefficients for measuring optimisation results expressed in activity duration reductions and activity cost reductions of the observed shipbuilding process, here depending on various modes of outfitting.

The particular optimisation of the shipbuilding process was performed through implementation of a modular outfitting concept. A developed procedure for measuring optimisation results demonstrated that, in

Table 6. Results for characteristic cases in implementation of modular outfitting concept

Tablica 6. Prikaz rezultata za karakteristične primjere primjene koncepta modularnog opremanja broda

	Analysed cases / Analizirani slučajevi	**Activity duration (working hours) / Trajanje aktivnosti (radni sati)**	**Total duration of shipbuilding process (working hours) / Ukupno trajane pocesa (radni sati)**	**Reduction of shipbuilding cost (%) / Smanjenje troškova (%)**	**Reduction of shipbuilding duration (%) / Skraćene trajanja procesa (%)**
1	Initial level of outfitting / Početna razina opremanja	1 512 500	544 900	0	0
2	Case 1 / Slučaj 1	1 437 548	496 552	5	9
3	Case 2 / Slučaj 2	1 370 924	453 576	9	17
4	Case 3 / Slučaj 3	1 398 391	457 619	8	16
5	Case 4 / Slučaj 4	1 292 610	375 709	15	31

observed case, it is possible by using this concept, to increase the outfit level of completion between observed and optimised state.

According to developed algorithm, it is possible to accomplish a decrease of shipbuilding costs up to15%, as well as shortening the time of shipbuilding process up to 31%.

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