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# Lean Manufacturing Methodology for Shipyards

Original scientific paper

Many shipyards today have made technological changes to their production facilities over the past decades. However, the building methodology has remained the same. Implementing a lean manufacturing approach to shipyards requires analysis of the present shipyard facilities. Likewise, the lean compliance level needs to be measured. After this, the steps for lean transformation are determined. In this work, a case study of a shipyard with a traditional panel-block assembly process is transformed to a lean one which follows one piece flow. The integration of group technology, a product work breakdown structure (PWBS) and lean manufacturing yields optimal results illustrated through risk analysis. This is best demonstrated through the analysis of man-hours in assembling a typical shipbuilding block ready for erection.

**Keywords:** *lean manufacturing, shipyard, product work breakdown structure, risk analysis*

## Metodologija vitke proizvodnje za brodogradilišta

Izvorni znanstveni rad

Mnoga brodogradilišta su napravila tehnološke promjene na proizvodnim postrojenjima kroz zadnja desetljeća. Međutim, metodologija sastavljanja međuproizvoda je ostala slična ili ista. Implementiranje pristupa vitke proizvodnje brodogradilištima zahtijeva analize trenutačnog stanja u brodograđevnim postrojenjima, i u isto vrijeme je potrebno mjeriti razinu sukladnosti prema vitkim načelima. Nakon toga treba poduzeti korake potrebne za vitku transformaciju. Stoga je na primjeru realnog brodogradilišta sa tradicionalnom linijom za izradu panela i kompletiranih panela primijenjena metodologija vitke transformacije u vitku liniju koja prati princip toka linije *one piece flow*. Integracija grupne tehnologije, tehnološke raščlambe odnosno strukture radne raščlambe (PWBS) i vitke proizvodnje, rezultira u optimalnim ishodima provjerenim analizom rizika. Isto je demonstrirano kroz analizu radnih sati potrebnih za sastavljanje tipičnog bloka trupa broda.

**Ključne riječi:** *vitka proizvodnja, brodogradilište, struktura radne raščlambe, analiza rizika*

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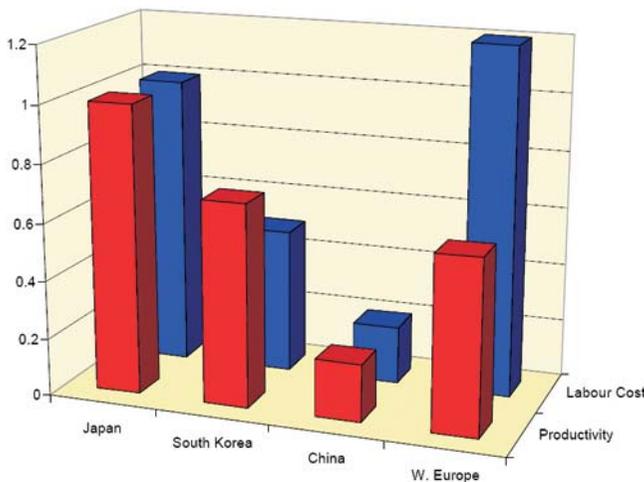
## 1 Introduction

Many shipyards have made certain technological improvements to their facilities over the past decades. However, these changes still have not raised the competitive level to those shipyards that are applying lean manufacturing techniques such as *Ishiwajima-Harima Heavy Industries (IHI)* or *Kawasaki* in Japan. The vessels built by these yards include those which most European yards consider unprofitable such as bulk carriers, oil tankers, container ships, Ro/Ro vessels, as well as vessels with higher CGT values such as LNGs and naval ships. Many European yards, which while improving technology to their shipyard processes, such as replacing two-sides welding on the panel assembly line with one-sided welding, have not made the lean methodological changes, such as incorporating one-piece flow in the panel assembly process, necessary for being competitive in the construction of various types of ships. The abandonment of commercial shipbuilding markets such as product tankers, or even bulk carriers have led to a decreased order book and the loss of mass customization techniques. Relying just on naval and special

vessels will not feed the order book necessary for the survival of shipyards. This is evident in both the US and Europe.

The basis for a lean manufacturing transformation of shipyard processes includes developing a case study of the present production facilities for a typical product mix of vessels in the production program. Shipyards which have a product work breakdown structure (PWBS) will be more receptive to adapting their production towards lean manufacturing. Group technology and design for production techniques make significant enhancements to shipyard processes. However, with the integration of lean manufacturing, the production facilities become even more efficient reducing man-hours up to 60% from the original state [1].

A case study of the panel-block assembly process was developed for a shipyard with a product mix. The interim product analyzed included double bottom blocks of three types of vessels. A type plan was developed for the present state at the shipyard. Using the lean principles of pull and one piece flow, the future transformed lean state was developed. Finally, the Monte Carlo method was used to aid in man-hour estimation and also to decrease risk in the decision making process as well.



Baseline = Japan (1.0)

Figure 1 Comparison of Japanese shipbuilding productivity and labor costs [2]

Slika 1 Usporedba produktivnosti japanske brodograđevne industrije i troškova radnika [2]

The above figure illustrates that Japanese shipyards which have come the closest to implementing lean manufacturing techniques in their processes are the most productive. “Strong proficiency in dimensional and accuracy control in international shipyards permits further automation, lower work content, and faster construction times”[3]. While Western Europe is less productive than South Korea, it is still more productive than China. With the advent of lean manufacturing implementation in Chinese shipyards, the situation will drastically change and Europe will find itself in a continually declining situation. Therefore, it is necessary for Europe and the United States, former powerhouses in shipbuilding just a few decades ago, to change their shipbuilding strategy. The adoption of lean manufacturing complemented with mass customization techniques will result in a return to the shipbuilding market through competitiveness [4], [5].

## 2 Panel-block assembly facilities

The key area for applying lean manufacturing is the panel-block assembly process. Analysis of the panel lines shows that much is lacking in terms of competitiveness. This includes one-sided welding of steel plates which is performed by all world-class competitive shipyards. This is just one technological improvement that is in line with lean manufacturing. However, actual lean manufacturing implementation requires the transformation of traditional panel lines and built up panel lines which still exist in many European shipyards. These lean principles include one-piece-flow manufacturing, along with takt time between stations, Just-in-Time and level production as well as built in quality. The combination of all of these lean principles results in time savings, and equally important if not more so, in man-hour reduction, which directly brings significant savings to the shipyard [6], [7].

### 2.1 Traditional panel-block assembly facilities

Table 1 below describes activities of the traditional panel-block assembly lines which exist in most European shipyards.

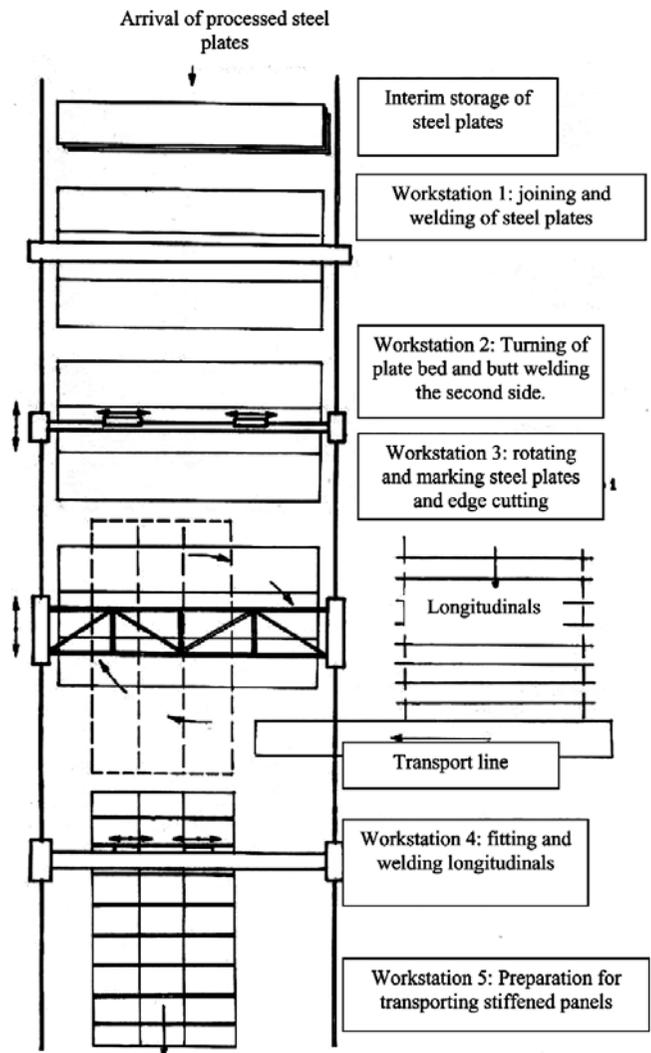


Figure 2 Illustration of a traditional panel line [8]  
Slika 2 Prikaz tipične linije za izradu panela [8]

Likewise, a typical takt time and total man-hours are listed in the right three columns with the coefficient calculated based on the number of workers, and numbers of panels and built-up panels in a typical double bottom block. Workstations 1 to 5 represent the panel line activities (Figure 2), while workstations 6 to 9 represent the built-up panel line activities (Figure 3).

Table 1 Activities of the panel-block workstations [1], [6]  
Tablica 1 Aktivnosti na radnim postajama linije za izradu panela i kompletiranih panela [1], [6]

| Present day panel-block assembly workstations |   |                   |                                     |                                     |
|---|---|-------------------|-------------------------------------|-------------------------------------|
| Station                                       | Description   | Takt time (hours) | Coefficient                         | Takt time x coefficient = Man-hours |
| 1   | Joining and welding of steel plates to form a plate blanket | 4                 | 4 seams x 2 workers x 4 panels = 32 | 128                                 |

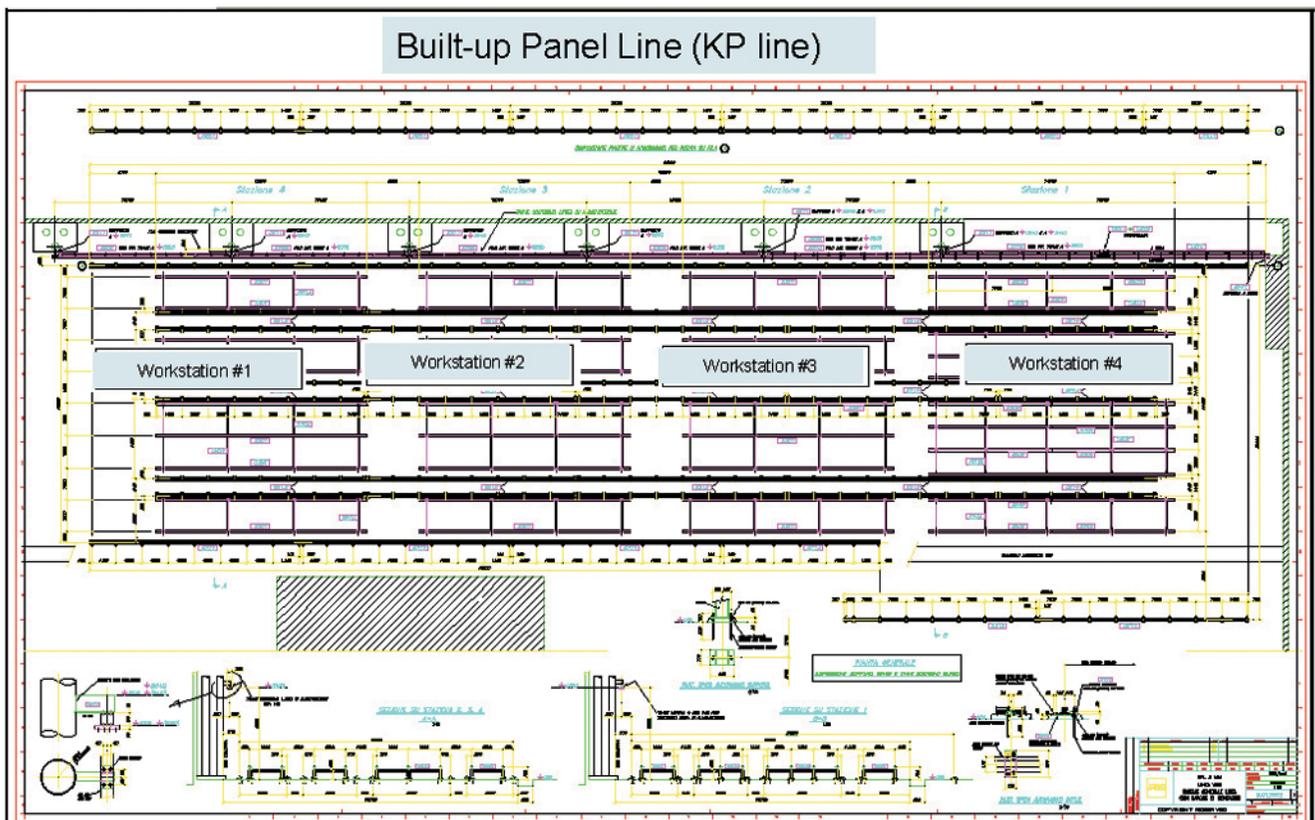
|   |   |   |                                     |     |
|---|---|---|-------------------------------------|-----|
| 2 | Plate blanket turned over and butt welded on the second side                  | 4 | 4 panels x 2 workers = 8            | 32  |
| 3 | Marking the plate blanket for longitudinal stiffeners, and ultrasound control | 4 | 4 panels x 2 workers = 8            | 32  |
| 4 | Fitting and welding of longitudinals  | 4 | 4 panels x 2 workers = 8            | 32  |
| 5 | Quality control and transportation to the built-up panel line                 | 4 | 4 panels x 1 worker = 4             | 16  |
| 6 | Turning and levelling with heat   | 8 | 2 built-up panels x 2 workers = 4   | 32  |
| 7 | Labelling, laying and tack welding of transverses                             | 8 | 2 built-up panels x 12 workers = 24 | 192 |

|  |   |    |                                     |      |
|--|---|----|-------------------------------------|------|
| 8  | Welding of transverses and cleaning the weld                            | 8  | 2 built-up panels x 12 workers = 24 | 192  |
| 9  | Grinding and preliminary outfitting                                     | 8  | 2 built-up panels x 10 workers = 20 | 160  |
| 10   | Final three-dimensional block assembly prior to erection on the slipway | 16 | 11 workers                          | 176  |
| Total man-hours for complete double block assembly |   |    |                                     | 1000 |

**2.2 Lean panel-block assembly facilities**

Whereas the one sided welding technology is implemented in the panel lines of the shipyards of most Western European countries, this in and of itself is not lean manufacturing. The implementation of one piece flow as opposed to creating large bed plates and then placing the longitudinals and welding is required. Determining steps necessary to transform traditional panel assembly to lean one-piece flow manufacturing is necessary. The

Figure 3 Illustration of a traditional built-up panel line [9]  
 Slika 3 Prikaz tipične linije za izradu kompletiranih panela [9]

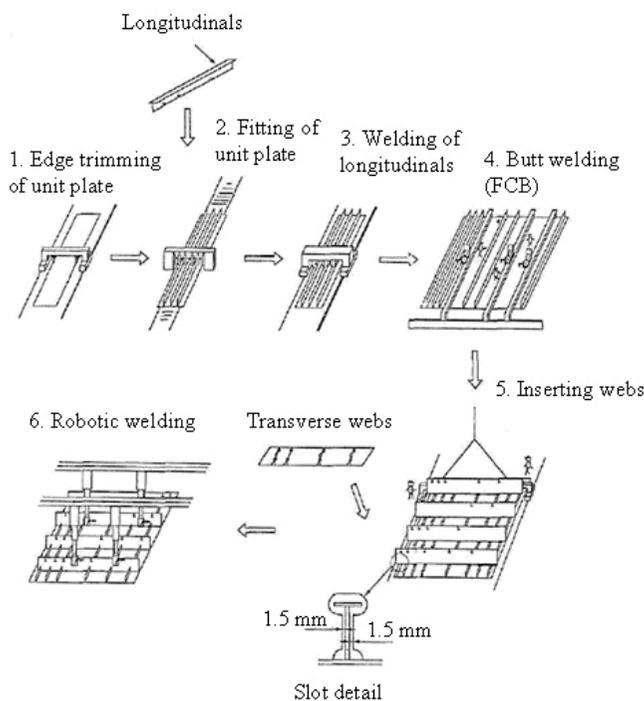


waste that is inherent in traditional panel lines and which can be eliminated in lean panel lines includes overproduction, waiting, unnecessary motions, overprocessing, transport and inventories, and defects. These are the seven wastes identified by performing lean analysis [10].

One piece flow in the shipbuilding panel and completed panel assembly lines is also known as a “unit panel and slit” process. Exclusively single steel plates which are between 1.5 to 4.5 m in width are accepted at the first workstation, where they are trimmed as necessary. Then up to four longitudinals are fitted on the unit panel “simultaneously using automated processes” [6]. At the third workstation, the longitudinals are simultaneously welded. Depending on how large the final stiffened panel is, the above described process at workstation three is repeated for up to six unit panels upon which the stiffened unit panels are then welded together using one-sided automatic welding technology also known as Flux Copper Backing (FCB) welding machines. The waste of *unnecessary motions* of turning over to weld on the second side is eliminated (See Figure 4).

At workstation 5 is the beginning of what traditional shipyards call the built-up panel process. Transverses that are subassembled in a previous micropanel process have slots instead of cut-outs. These transverses are pushed with special pushing equipment instead of being placed over as in traditional shipyards. This step requires high precision and accuracy control to be inherent in the action. The use of slots instead of cut-outs eliminates the need for lugs. Lug fitting can be considered as a wasteful action which requires unnecessary motions. Likewise, the elimination of lugs means that the strength of the panel is also improved. Finally, the use of robotic welding in workstation 6 additionally improves the manufacturing process by reducing man-hours and duration time for assembly (See Figure 4).

Figure 4 Unit panel and slot assembly method [11]  
Slika 4 Metoda jedinične panele s utorima [11]



### 3 Lean transformation of shipbuilding block assembly

In order to achieve a lean transformation of traditional block assembly it is necessary to integrate both the one piece flow principle with leveled production also known as *heijunka*. As witnessed above, the traditional panel-block assembly process does not have an equal takt time between workstations. This results in *mura* or unevenness, which can only be developed through a lean transformation. This in turn requires that interim products arrive Just in Time (JIT) as the example with the transverses arriving JIT at workstation 5 from the micropanel assembly line. The use of a PWBS shipyard organization enables the continually repetitive nature of assembled interim products such as unit panels and transverses, which form larger blocks when assembled together (See Figure 5).

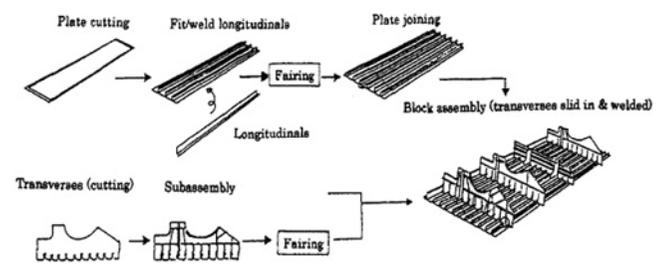


Figure 5 Unit panel and slot construction [12]  
Slika 5 Konstrukcija jedinične panele s utorima [12]

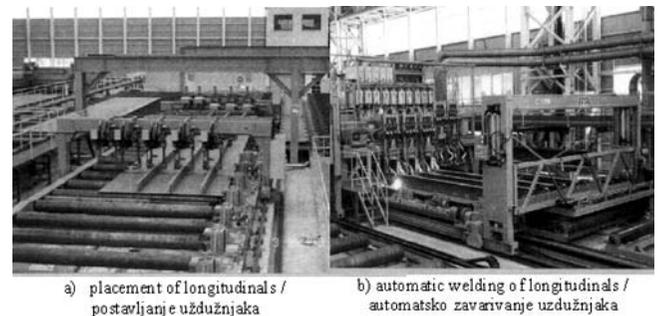


Figure 6 Unit panel and slot construction – automatic placement and welding of longitudinals [12]  
Slika 6 Konstrukcija jedinične panele – automatsko postavljanje i zavarivanje uzdužnjaka [12]

Longitudinals are automatically fitted on panels where there is only one operator (See Figure 6a). This is in contrast to the traditional panel line where longitudinals are fitted one by one, which means that the man-hours are at least three to four times greater. At the next workstation, the same longitudinals are automatically welded with only one operator present at the control panel. Again, the traditional panel line approach welds the longitudinals one by one by at least two to three workers at the station. Therefore, in the traditional panel line, the welding duration times are four times greater as are the man-hours (See Figure 6b).

At the next workstation, the transverses are pushed through the longitudinals in a smooth motion (See Figure 7). Here again there is a decrease in both duration time and man-hours in com-



Figure 7 Unit panel and slot construction – sliding on transverses [12]

Slika 7 Konstrukcija jediničnih panela s utorima – navlačenje rebrerice [12]

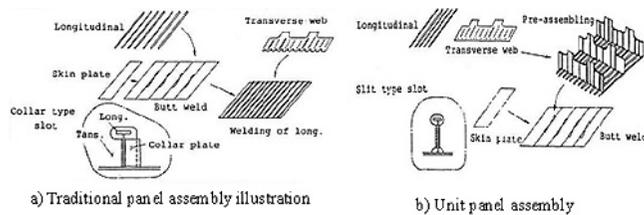
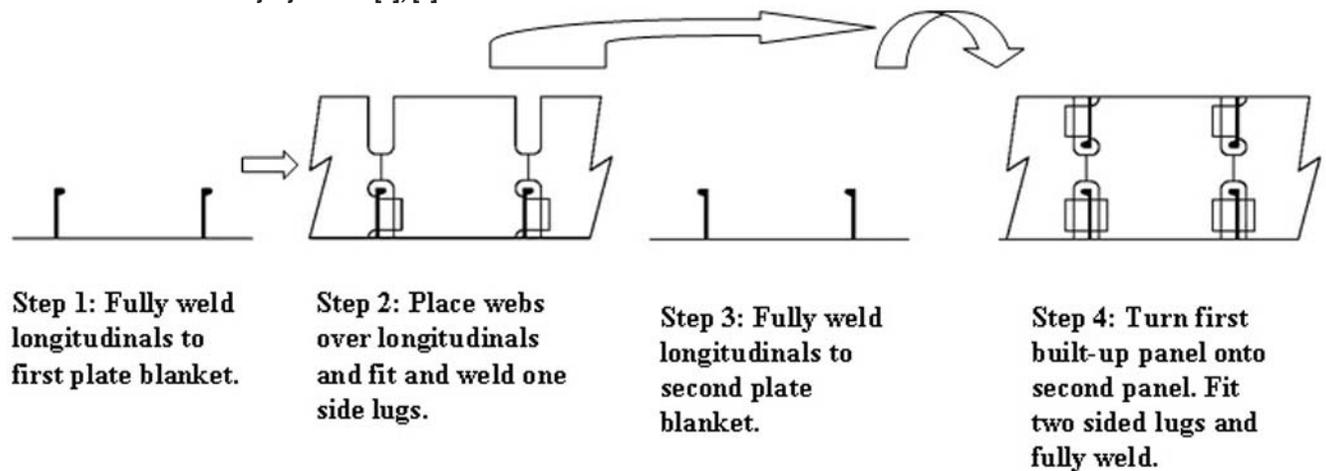


Figure 8 a) Traditional panel assembly vs. b) Unit panel assembly illustration [11]

Slika 8 a) Tradicionalna montaža panela vs. b) Montaže jedinične panele [11]

Figure 10 Block assembly method [1], [6]  
Slika 10 Metoda sastavljanja bloka [1], [6]



**Step 1: Fully weld longitudinal to first plate blanket.**

**Step 2: Place webs over longitudinal and fit and weld one side lugs.**

**Step 3: Fully weld longitudinal to second plate blanket.**

**Step 4: Turn first built-up panel onto second panel. Fit two sided lugs and fully weld.**

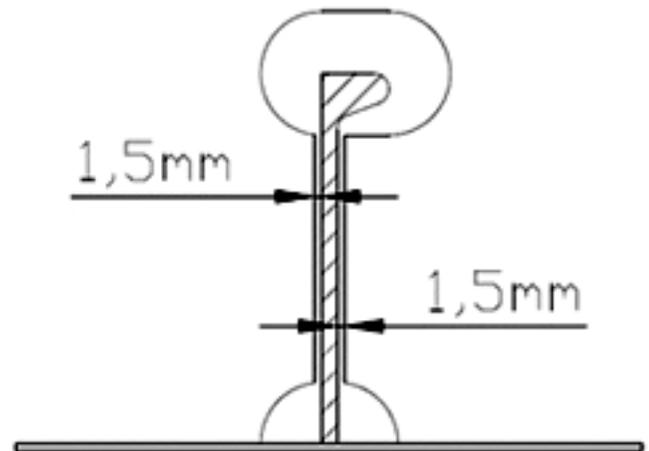


Figure 9 Detail of slot for a bulb profile [6]  
Slika 9 Detalj utora za bulb profil [6]

parison to the traditional panel line, because of the elimination of lugs, which significantly reduces welding (See Figure 8a and 8b). The pushing of the longitudinals makes use of built-in quality, another principle of lean manufacturing, because the slot has as a minimal clearance of 1.5 mm, which translates to performing quality control during assembly (See Figure 9). This is in contrast to the traditional built-up panel line where work has to be halted for quality control to do its job due to the cut-outs which inherently require additional steps in making sure that the transverse is placed in the proper spot. The non-added value work of additional accuracy control is eliminated in the lean process due to the built in quality characteristics of the lean procedure of transverse fitting.

The traditional shipyard block assembly method includes fully welding longitudinals to the first plate blanket in step 1. In step 2 the webs are placed over longitudinals, fitted and one side lugs are welded, which results in a built up panel. Another bed plate is fully welded to the longitudinals to form the second panel. Finally, in step 4 the built up panel is turned onto the second panel and fully welded (See Figure 10).

The lean manufacturing method of block assembly includes panels with fully welded longitudinals in step 1. However, in

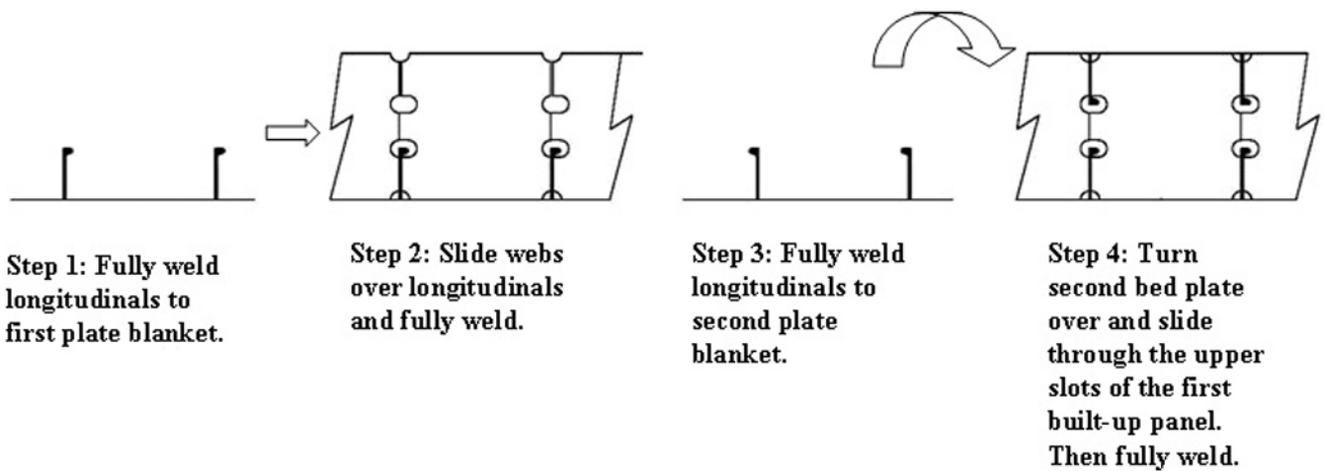


Figure 11 Lean manufacturing panel-block assembly method [1], [6]  
 Slika 11 Vitka metoda sastavljanja bloka [1], [6]

step 2 transverses are slid or pushed over the longitudinals and fully welded. In step 3, there is the assembly of a fully welded panel. Finally in step 4, the second bed plate is turned over and slid through the upper slots of the first built up panel of step 2, and then fully welded (See Figure 11).

Table 2 Activities of the lean panel-block workstations [1], [6]  
 Tablica 2 Aktivnosti na radnim postajama vitkih linija za izradu panela i blokova [1], [6]

| Lean transformation of panel-block assembly workstations |   |                   |   |                         |
|--|---|-------------------|---|-------------------------|
| Station  | Description   | Takt time (hours) | Coefficient                                   | Takt time x Coefficient |
| 1  | Edge trimming of the unit plate   | 1                 | 5 unit plates x 4 panels x 2 workers = 40     | 40                      |
| 2  | Fitting of longitudinals on the unit panel  | 1                 | 5 unit plates x 4 panels x 2 workers = 40     | 40                      |
| 3  | Welding of longitudinals  | 1                 | 5 unit plates x 4 panels x 2 workers = 40     | 40                      |
| 4  | One sided butt welding - FCB (Flux copper backing welding)                                      | 1                 | 4 one sided seams x 4 panels x 2 workers = 32 | 32                      |
| 5  | Inserting of internal structure (egg-crate) with slots assembled on a matrix off the worksation | 4                 | 2 built-up panels x 20 workers = 40           | 160                     |
| 6  | Welding of egg-crate by robots  | 4                 | 2 built-up panels x 5 workers = 10            | 40                      |
| 7  | Final three dimensional block assembly prior to erection on the slipway                         | 4                 | 12 workers                                    | 48                      |
| Total man-hours for block assembly                       |   |                   |   | 400                     |

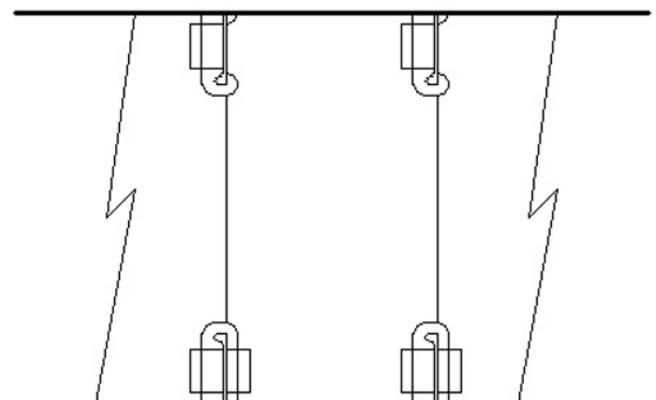
The equipment necessary for a lean transformation of a traditional panel-block assembly process explained in Table 2 above, which is also recommended for the shipyard of this case study includes the following [1], [6]:

1. High-grade fitting machine for fitting up to 4 longitudinals simultaneously at lean workstation 2,
2. Automatic welding machines (4 pieces) on girder for welding longitudinals on both sides simultaneously at lean workstation 3,
3. One side automatic Flux-Copper Backing (FCB) x 3 machines at lean workstation 4,
4. Pushing type insert equipment at lean workstation 5,
5. Portable welding robots (4 pieces) which are hung down from two girders at lean workstation 6.

#### 4 Interim product work content analysis in block assembly

Since it is clear how panel-block assembly processes function in traditional shipyards, and how a lean transformation can be performed, shipyard management will be best enticed to undertake measures to undergo the transformation upon performance

Figure 12 Category 1, block assembly method [6]  
 Slika 12 Kategorija 1, metoda sastavljanja bloka [6]



of a work content analysis which is proof of a reduction of man-hours. This translates to an increase in savings and profit. Design for production (DFP) analysis which includes a work content analysis is used by consultants in shipyards which decide to do the transformation [6], [13]. The following four categories which represent a cross section of viable block assembly options were used for the work content analysis in block assembly.

In category 1, transverses with cut-outs are placed over longitudinals and then welded. The upper longitudinals have a lug on one side. The lower longitudinals have lugs on both sides. This category represents the traditional block assembly method still used in many shipyards (See Figure 12).

In category 2 there is a built up panel assembled in the traditional way with cut-outs in transverses while the second panel is slid through slots (See Figure 13).

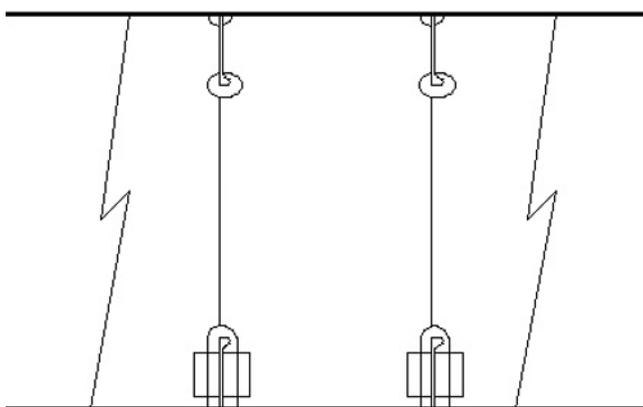


Figure 13 **Category 2, block assembly method [6]**  
Slika 13 **Kategorija 2, metoda sastavljanja bloka [6]**

In category 3 transverses are slid over the longitudinals. Then upper longitudinals are slid through the upper slots in the transverses and fitted. Finally, the built-up base panel is turned over onto a corresponding bed plate and welded (See Figure 14).

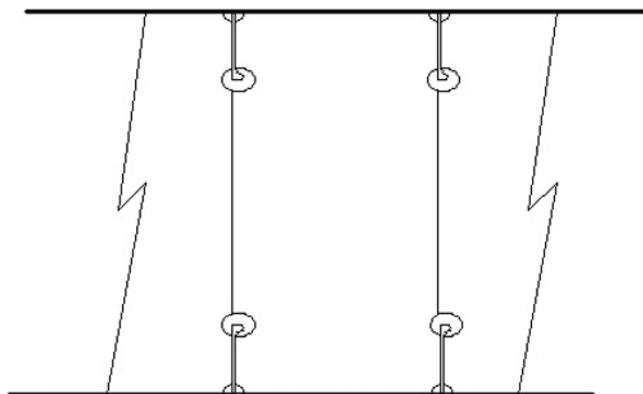


Figure 14 **Category 3, block assembly method [6]**  
Slika 14 **Kategorija 3, metoda sastavljanja bloka [6]**

In category 4 all longitudinals are pushed through fitted slots in transverses assembled in a matrix jig off the panel line (See Figure 15).

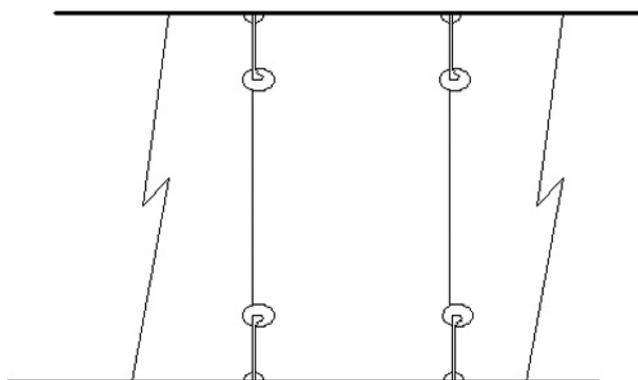


Figure 15 **Category 4, block assembly method [6]**  
Slika 15 **Kategorija 4, metoda sastavljanja bloka [6]**

In continuation of the analysis it is necessary to choose a generic block with the following characteristics (See Figure 16) [13]:

|                                    |                                     |
|------------------------------------|-------------------------------------|
| Block type:                        | Double bottom section               |
| Block size:                        | Length (m) x Width (m) x Height (m) |
| No. of panels:                     | 4 or 5                              |
| No. of plates / panel:             | 4 or 5                              |
| No. of longitudinals / panel:      | 10 to 14                            |
| No. of transverse members / panel: | 3-5                                 |

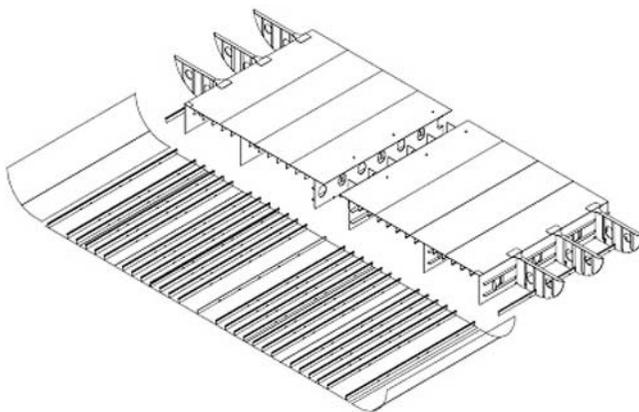


Figure 16 **Typical double bottom block of a tanker [6], [14]**  
Slika 16 **Tipična sekcija dvodna tankera [6], [14]**

Table 3 **Summary of work content analysis**  
Tablica 3 **Sažetak analize radnog sadržaja**

| Category | Weld Length (m) | Man-hours (hr) | Percentage increase from Category 1 from DFP manual |
|----------|-----------------|----------------|---|
| 1        | 916             | 1000           | 0%  |
| 2        | 900             | 1050           | 5%  |
| 3        | 776             | 1240           | 24%   |
| 4        | 776             | 1300           | 30%   |

In Table 3 above, Category 1 represents a generic double-bottom block with 1000 man-hours of assembly time as explained in detail in Table 1 above. The precise takt time, man-hour values

and actual dimensions are not to be disclosed due to reasons of confidentiality. However, the method is explained since the takt time multiplied by the appropriate coefficient yields the man-hours. The ranges and percentage increases are accurate so that a similar type of analysis can be performed by simply updating the Category 1 value. For Categories 2 to 4, the man-hour values are calculated based on the percentage increases from the DFP manual for a traditional shipyard with fixed technology but changing assembly methodology, see the right-most column of Table 3. The present method of assembly at the shipyard is in compliance with category 1 which is the standard DFP method used in traditional shipyards as identified by the case study in the DFP manual [13]. The rest of the values are interpolated accordingly.

Table 3 above demonstrates that as the block assembly categories change from 1 to 4, the amount of weld length decreases. This is due to the cut-outs in the transverses changing to slot or slit-type openings. Initially unexpectedly, however, the man-hours increase. This is because of the implementation of slots on the traditional panel-block assembly lines which do not possess the complementary technology for efficient assembly. The use of slots instead of cut-outs requires a different production technology, particularly in accuracy control and specific manufacturing sequences that are level and balanced. Only when the technology of the entire panel-block assembly is altered and adjusted to meet the demands of the slot methodology can there be a reduction in man-hours, which is logical given that the weld length has decreased.

**5 Risk analysis of block assembly methods**

The perspective of understanding the different categories in shipbuilding has lead to a need to develop a method to decrease the risk in panel-block assembly decision making. Likewise, the large variation in man-hours directly affects the financial status of the shipyard [15]. A methodology useful for shipyard management in order to decrease the risk of strategic decisions, of which the panel-block assembly process is one since up to 70% of shipyard blocks are processed through automated process lines. It is risky for top management not to understand the building methodology which is an integral part of the shipyard strategy.

**5.1 Risk analysis with the PERT distribution and Monte Carlo simulation**

Risk analysis using Monte Carlo simulation is relatively new in shipbuilding [1], [16], [17]. However, since there are more than 56 combinations for assembling a typical shipbuilding block, it is necessary for shipyard management to have access and understanding of this through risk analysis [6]. The combining of the PERT distribution along with Monte Carlo simulation enables an effective way to estimate man-hours during block assembly. Since the situation in most shipyards rarely leads to the prediction of exact man-hour values even by the most experienced and skilled engineers, it is necessary to couple both the experience of the engineers in a mathematical model such as the PERT distribution, which when integrated with a Monte Carlo simulation enables a very realistic picture of the range of possibilities, and the most likely man-hour values of the four different block assembly categories illustrated above See figures 12 to 15). The PERT distribution appears like the normal distribution. However,

it resembles a more realistic probability distribution (See Figure 17). The left distribution is a normal distribution while the right curve represents a PERT distribution.



Figure 17 Examples of the PERT distribution [18]  
Slika 17 Primjeri PERT razdiobe [18]

With the use of the standard Excel program along with an @ risk add on, it is possible to make use of expert man-hour values in a PERT distribution framework and finally engage with Monte Carlo simulation [19], [20], [21]. The standard command used in the above compilation is:

$$= \text{RISKPert} (\text{Lower bound value}, \text{Most likely value}, \text{Upper bound value}) \tag{1}$$

In the PERT distribution, the mean  $\mu$  is calculated [20]:

$$\mu = \frac{(X_{\min} + X_{\max} + 4X_{\text{most likely}})}{6} \tag{2}$$

$$\sigma^2 = \frac{(X_{\min} - X_{\max})^2}{36} \tag{3}$$

$$\sigma = \text{sqrt} (\sigma^2) \tag{4}$$

The mean value ( $\mu$ ) is calculated from the lower bound  $X_{\min}$ , upper bound  $X_{\max}$  and most likely  $X_{\text{most likely}}$  values where  $\sigma^2$  = variance;  $\sigma$  = standard deviation.

**5.2 Risk analysis enhancement with Monte Carlo simulation in block assembly**

Using Table 3 with man-hour values for the four different categories for block assembly using DFP methods, and then the value of assembly values of iterim products using *lean manufacturing* methods, the table necessary for risk the analysis of all categories is created below (See Table 4).

The Monte Carlo simulation was performed using the @ RISK add-on for Excel from Palisades Corporation. Monte Carlo simulation seen in Table 4 is done to perform “random variate generation” of values within a PERT distribution which results in more probable real world values [20]. The values of the 4 categories derive from Table 3 described earlier. The Fixed / Changing Line Technology (F/CLT) row  $X_{\min}$  is 700 man-hours, based on a 30% improvement over the 1000 man-hours of Category 1. This occurs as a result of making required technology adjustments in complement to methodology adjustmensts of the DFP manual

Table 4 Risk analysis table  
 Tablica 4 Tablica analyze rizika

| Block Assembly Method Category | $X_{\min}$ | $X_{\text{most likely}}$ | $X_{\max}$ | $s^2$<br>Theor.        | $s^2$<br>Exper.        | $s$<br>Theor. | $s$<br>Exper. | $\mu$<br>Exper. |
|--------------------------------|------------|--------------------------|------------|------------------------|------------------------|---------------|---------------|-----------------|
|                                | Man-hrs    | Man-hrs                  | Man-hrs    | (Man-hrs) <sup>2</sup> | (Man-hrs) <sup>2</sup> | Man-hrs       | Man-hrs       | Man-hrs         |
| FLT Category 1                 | 950        | 1000                     | 1050       | 277,8                  | 351,31                 | 16,67         | 18,74         | <b>999,53</b>   |
| FLT Category 2                 | 997.5      | 1050                     | 1102.5     | 306,3                  | 393,31                 | 17,50         | 19,83         | <b>1050,78</b>  |
| FLT Category 3                 | 1178       | 1240                     | 1302       | 427,1                  | 540,95                 | 20,67         | 23,26         | <b>1240,49</b>  |
| FLT Category 4                 | 1235       | 1300                     | 1365       | 469,4                  | 593,44                 | 21,67         | 24,36         | <b>1298,74</b>  |
| F/CLT                          | 700        | 1000                     | 1300       | 10000                  | 12626,82               | 100           | 112,37        | <b>1004,56</b>  |
| Lean Transformation            | 380        | 400                      | 420        | 44,44                  | 60,85                  | 6,67          | 7,80          | <b>400,27</b>   |

#### Legend of Table 4

FLT Category 1: Fixed Line Technology of Category 1,  
 FLT Category 2: Fixed Line Technology of Category 2,  
 FLT Category 3: Fixed Line Technology of Category 3,  
 FLT Category 4: Fixed Line Technology of Category 4,  
 F/CLT: Fixed/Changing Line Technology,  
 Lean Transformation

$X_{\min}$  = lower bound value

$X_{\max}$  = upper bound value

$X_{\text{most likely}}$  = most likely value =  $\mu$  theoretical

$s^2_{\text{Theor.}}$  = theoretical variance explained in equation 3 above

$s_{\text{Theor.}}$  = theoretical standard deviation explained in equation 4 above

$s^2_{\text{Exper.}}$  = experimental variance received from Monte Carlo simulation

$s_{\text{Exper.}}$  = experimental standard deviation received from Monte Carlo simulation

$\mu_{\text{Exper.}}$  = experimental mean value obtained from Monte Carlo simulation

[13]. The  $X_{\max}$  value of 1300 represents the most likely values of Category 4 which has the highest man hours due to technology not being updated with the changing advanced technology.

Please note that the upper and lower bound values of Table 4 are obtained by adding and subtracting 5% of the most likely value. Due to experience with shipyards that have a product work breakdown structure (PWBS), the authors decided to use 5% based on experience in manufacturing at the shipyard and with similar type shipyards. Vessels at the shipyard are built on time, and the present automated processes while traditional, likewise follow work norms.

$$X_{\min} = X_{\text{most likely}} - 5\% \text{ of } X_{\text{most likely}} \quad (5)$$

$$X_{\max} = X_{\text{most likely}} + 5\% \text{ of } X_{\text{most likely}} \quad (6)$$

In Table 4 the  $X_{\min}$  represents the lower bound values;  $X_{\max}$  represents the upper bound values and  $X_{\text{most likely}}$  represents the most likely inputted values for each category. The theoretical variance  $\sigma^2$  and theoretical standard deviation  $\sigma$  are different from the experimental or Monte Carlo simulation results of variance and standard deviation. The experimental mean  $\mu$  is also different from the theoretical mean which is the same as the most likely value in Table 4.

- FLT Category 1 represents the Fixed Line Technology of the traditional block assembly method. The most likely value of 1000 man-hours derives from Category 1, line technology of Table 3. The lower and upper bound values of 950 and 1050 respectively are approximately  $\pm 5\%$  of the Category 1 value of 1000 man-hours for line technology.
- FLT Category 2 represents the Fixed Line Technology with a combination of cut-outs and slots described earlier. Again the most likely value of 1050 man-hours is taken from Table 3. The lower and upper bound values of 997.5 and 1102.5 are

approximately  $\pm 5\%$  of the Category 2 value of 1050 man-hours.

- FLT Category 3 is the Fixed Line Technology of the block assembly method with slots instead of cut-outs in the transverses. The most likely value of 1240 man-hours is taken from Table 3. The lower and upper bound values are approximately  $\pm 5\%$  of the Category 3 value of 1240 man-hours for line technology.
- FLT Category 4 is the Fixed Line Technology of Category 4. The most likely value of 1300 man-hours is also taken from Table 3. The lower and upper bound values are approximately  $\pm 5\%$  of 1300 man-hours.
- F/CLT is the Fixed/Changing Line Technology illustration of all four categories. The upper bound value of 1300 man-hours represents the highest man-hour value from Table 3 of Category 4. The lower bound value of 700 man-hours is a 30% decrease from the Category 1 value of 1000 man-hours [13]. The expected improvement is 30% when technology and the appropriate complementary methodology are adjusted simultaneously [6].
- The lean transformation most likely value derives from a Gantt chart analysis of one piece flow with FCB one sided welding technology [6]. The lower and upper bound values are again  $\pm 5\%$  of the most likely value.

Fixed line technology of Category 1 uses the traditional panel line as described in section 2 earlier in this work. The simulation yields **999.53** man-hours (See Figure 18). Category 2 is a fixed line technology where the expected man hours are **1050.78** hours. Whereas Category 2 has a smaller weld length than Category 1, the man hours have increased instead of decreased (See Figure 19). Category 3 yields an even greater man-hour value of **1240.488** hours (See Figure 20). The results of the Category 4 simulation lead to a further increasing value of **1298.744** man hours. The four categories show that by maintaining the tech-

nology level of the panel line fixed, and only altering initially perceivable superior methods, the man-hours increase instead of decreasing (See Figure 21).

The Fixed/Changing Line Technology curve serves to demonstrate the simulation of all four categories as one curve. The

simulation shows a mean value of **1004.55** man-hours. To the left of the mean value, the man-hours decrease and approach **700** hours (See Figure 22). This is the situation which occurs when the technology of the panel-block line is adjusted to be compliant to the changing and improved slot technology. Go-

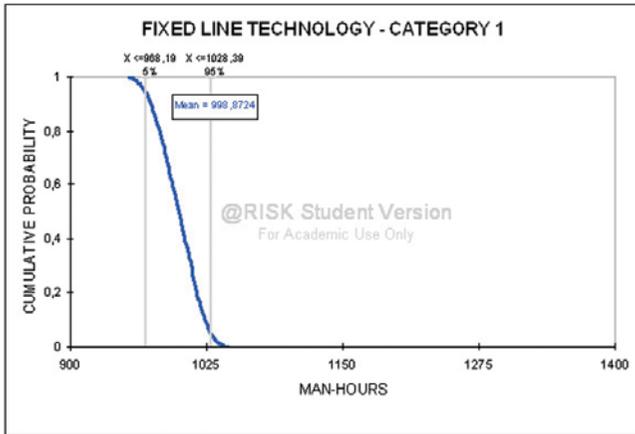


Figure 18 Fixed line technology - Category 1  
Slika 18 Fiksna linijska tehnologija - Kategorija 1

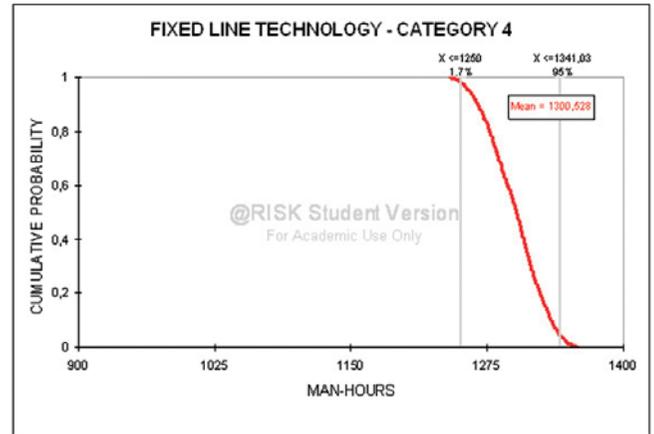


Figure 21 Fixed line technology - Category 4  
Slika 21 Fiksna linijska tehnologija - Kategorija 4

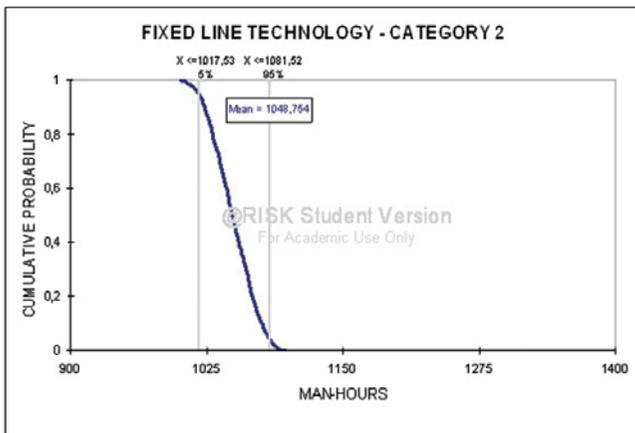


Figure 19 Fixed line technology - Category 2  
Slika 19 Fiksna linijska tehnologija - Kategorija 2

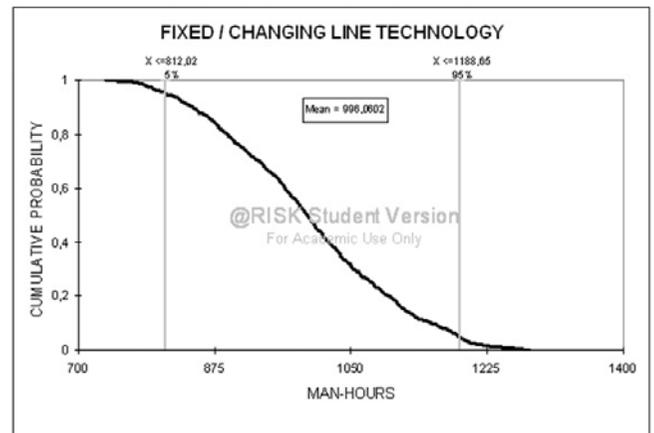


Figure 22 Fixed/Changing line technology  
Slika 22 Fiksna/promjenjiva linijska tehnologija

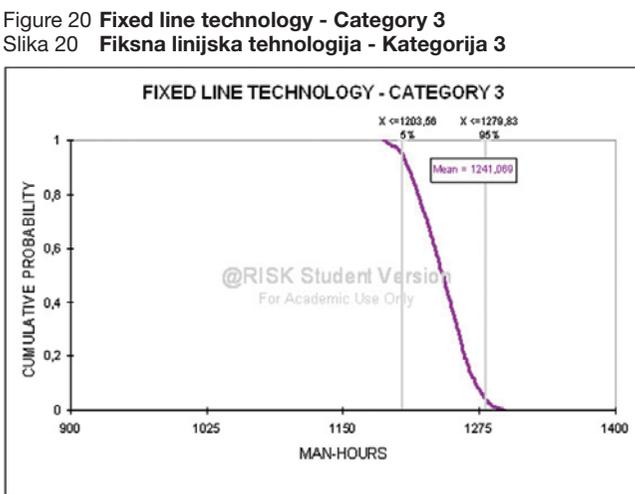


Figure 20 Fixed line technology - Category 3  
Slika 20 Fiksna linijska tehnologija - Kategorija 3

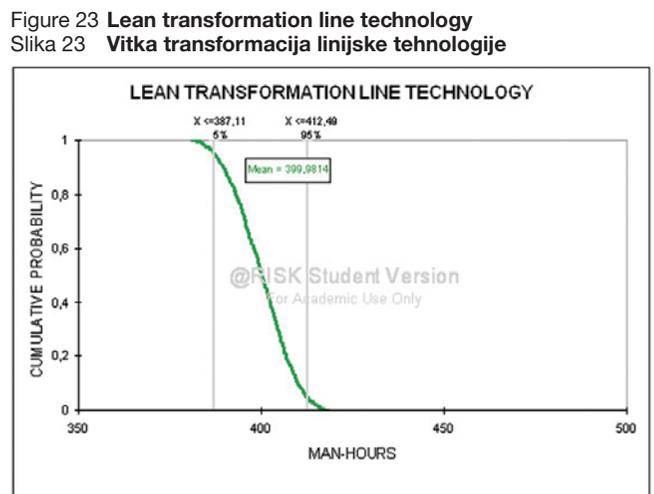


Figure 23 Lean transformation line technology  
Slika 23 Vitka transformacija linijske tehnologije

ing to the right of the mean value, results in higher man-hours towards **1300**. This occurs when the technology of the panel-block line remains fixed, while improving methods. Finally, the Lean Transformation Line Technology curve illustrates the mean value of **400.28** man-hours, which is close to the calculated value of 400 man-hours (See Figure 23). When the shipyard management decides to transform both the technology and complementary methodology, only then can we expect a **60% decrease** from the original 1000 man-hours of the present state technology and methodology.

## 6 Discussion of results

The mean values of the Category 1 to the Category 4 curves increase from 999.23 man-hours all the way to 1298.74 man-hours. This is due to the fact that when the technology level of the shipyard panel-block assembly process remains fixed as is the situation in many shipyards that have still not moved towards lean manufacturing implementation, the better methodology will not be utilized in a compliant manner. For example Category 2 includes a combination of fitted slots and cut-outs instead of exclusively cut-outs in its transverses. The assembly of transverses with fitted slots instead of cut-outs is less efficient for the fixed state technology level of the shipyard.

In Category 3 of Figure 20, where slots completely replace cut-outs in transverses, the mean value of the man hours increases to 1240.49 man-hours. This is a 24 percent increase over the Category 1 value of 999.53 man-hours in Figure 16. The result is an increase in difficulties of assembling all transverses with slots instead of cut-outs. In Category 4, Figure 21, in addition to transverses with slots, there is a requirement for a matrix off the standard line where transverses are assembled. The increase is 30 percent from 999.53 man-hours to 1298.74 man-hours. The complication is a result of the matrix off the workstation which forces workers to try to adjust both slot and matrix methodology with the same fixed technology level.

The purpose of Figure 22 is to illustrate the behavior of both a fixed level technology of the panel line and a transformation of the technology necessary to complement the slot assembly methodology. The mean value of 1004.56 man-hours is close to the 1000 man-hours of Category 1 and is used in the comparisons. Right of the mean value of 1004.56 man-hours, illustrates the man hour values from figures 19-21. Left of the mean illustrates how a step by step change of the technology level to complement the slot methodology change yields incremental decreases in man-hours. Since Category 4 has the least amount of weld length and the internal structure with slots is assembled on a matrix off the panel line, the result is that lean principles of JIT and level production result in a significant decrease in man-hours of 30 percent.

Finally, Figure 21 shows the Lean Transformation Line Technology which has the greatest man-hour savings of 60 percent. Whereas there are many similarities between Figures 23 and 22 due to the application of complete slot technology along with matrix off panel assembly, the superiority of the lean transformation over the DFP adjustment is due to one piece flow as well as a decrease in transport and the application of welding technologies such as FCB as well as the application of a PWBS which includes the use of detailed Gantt charts.

## 7 Conclusions

Whereas DFP has its place in panel-block assembly processes, lean transformation is simply the winner. This is due to the integration of group technology, and one piece flow as well as built-in quality and JIT manufacturing, which is lacking in other processes. The result is that lean manufacturing when implemented properly best arranges the processes which appear as factory like production which is worker friendly and technological. This results in a decrease in both duration time and man-hours as well as in a decrease of necessary space in the shipyard. The significant savings confirmed by the risk analysis is a proof to shipyard management that lean thinking and lean manufacturing is the way to be competitive in the international shipbuilding market.

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## Nomenclature

|       |   |
|-------|---|
| CGT   | - compensated gross tonnage                             |
| DFP   | - design for production                                 |
| FCB   | - flux-core butt  |
| FLT   | - fixed line technology                                 |
| F/CLT | - fixed/changing line technology                        |
| HP    | - bulb profile  |
| IHOP  | - integrated hull construction, outfitting and painting |
| KP    | - built up panel  |
| PWBS  | - product work breakdown structure                      |

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Deadlines and key dates

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|--|---------------|---------------|
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| Obavijest o prihvaćanju<br>Acceptance notification                       | 01.-12.-2012. | 15. 02. 2012. |
| Konačno slanje referata<br>Final submission of papers                    | 01.-04.-2012. | 01. 05. 2012. |
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