ISSN 0554-6397
Izvorni znanstveni članak
(*Original scientific paper*)

**Viktor Ložar**
E-mail: viktor.lozar@fsb.hr
**Neven Hadžić**
E-mail: neven.hadzic@fsb.hr
**Tihomir Opetuk**
E-mail: tihomir.opetuk@fsb.hr
**Robert Keser**
E-mail: robert.keser@fsb.hr
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia

# The Estimation of the Production Time for Steel Hull Elements Using the Finite State Method

## Abstract

The steel hull process of a shipyard transforms steel plates and profiles into elements needed to build the ship hull and superstructure. The production time for these elements is the basic input to schedule the whole shipbuilding process. Therefore, it is important to implement time estimation approaches based on production system engineering.
In this study, the recently developed finite state method for serial and splitting lines is employed to describe the steel hull process of a shipyard semi-analytically. Two typical ship sections are chosen to estimate the corresponding key performance indicators as the production rate, the work in process, and probabilities of starvation and blockade. The production time is estimated based on the production rate and the cycle time. These results are compared to the results obtained through a simulation approach using the software tool Enterprise Dynamics. The conclusion highlights the advantages and disadvantages of both approaches.

**Keywords**: steel hull process, production system engineering, key performance indicators, production time, finite state method

## 1. Introduction

Major shipyards consist out of various sub-processes as the production planning, the steel hull process, the manufacturing of the ship equipment, the ship section pre-assembly, the ship equipment pre-assembly, the ship hull assembly and launching, the ship outfitting and finishing and the ship testing and handover [1]. All these processes can be designed by the production system engineering approach which has been developed in the past five decades, mainly in the automotive industry [2]. This approach can be divided into an analytical approach, numerical approach, and semi-analytical approach.

In this research the main goal is the estimation of the production time for the steel hull process which defines the amount of time to produce all steel elements for the considered sections of a ship. Therefore, a semi-analytical approach will be employed, namely the finite state method, to determine the key performance indicators such as the production rate, the work in process, the probabilities of starvation and blockade. The results are compared with the numerical approach using the software tool enterprise dynamic.

## 2. The finite state method

The finite state method has been successfully validated against the analytical approach in the case of serial and splitting lines [3]. In this chapter a brief description about the finite state method for serial and splitting lines in the production steady state will be given.

The finite state method will be applicable only if the following assumptions are fulfilled: (a) status of each machine is determined independently, (b) the cycle time of machines is similar, (c) the time the machine is down is a multiple of the cycle time, (d) failure of the machine can happen only at the beginning of the cycle, (e) the first machine is never starved and the last machine is never blocked, (f) all input parts are equivalent with the output parts.

The finite state models of a serial line consist out of machines (circles) and buffers (rectangles), arranged in a line as shown in Figure 1. The models for splitting lines are build-up of several serial lines which are arranged in a main branch and secondary branches as shown in Figure 2.

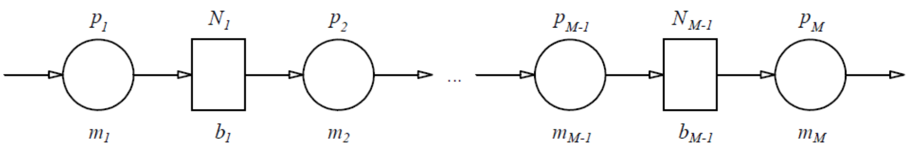


*Figure 1: Arrangement of a serial line [3]*

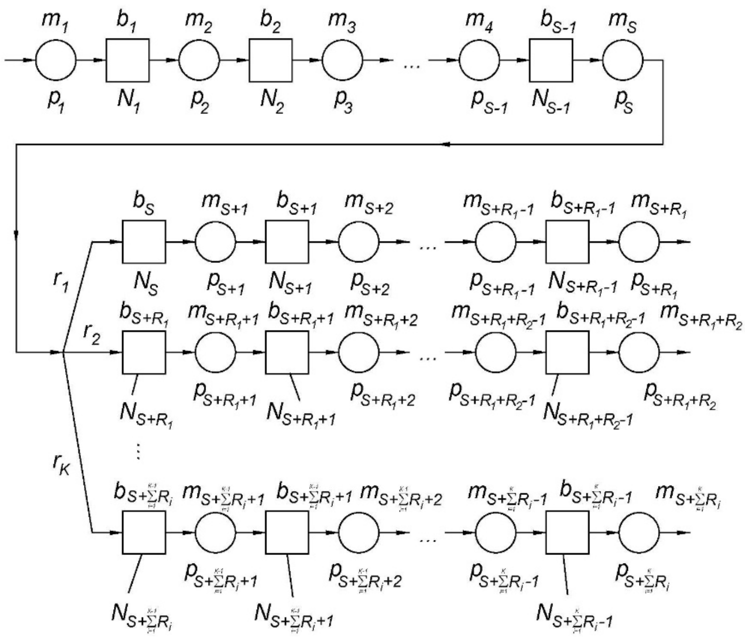


Figure 2: Arrangement of a splitting line [4]

The finite state method for serial lines and splitting lines basically break down the whole production process into elements which consist out of two machines and one buffer, where one machine always is the weakest machine, $p_m$, in the line or branch, see Figure 3.

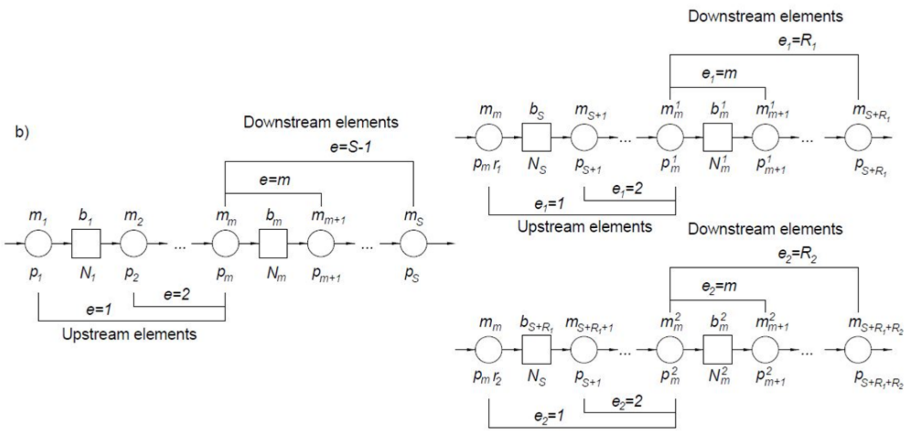


Figure 3: Elements of a splitting line [4]

For each element the eigenvector can be calculated by using the analytical expressions from Sevast'yanov, [5]. In a further step the eigenvector of the whole production process is calculated by multiplying the eigenvectors of each single element. The elements of the eigenvector of the whole production process represents the probability of each system state. The system state represents the status of each buffer in the production process [6].

Once the eigenvector of the whole system is determined the key performance indicators for serial lines can be computed by using the following expressions:

$$PR = p_M \left(1 - \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \dots \sum_{h_{M-1}=0}^{N_{M-1}} P_{h_1 h_2 h_3 \dots h_{M-1}}\right), \tag{1}$$

$$WIP_i = \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \dots \sum_{h_{M-1}=0}^{N_{M-1}} h_i P_{h_1 h_2 h_3 \dots h_{M-1}}, \tag{2}$$

$$BL_i = p_i \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \dots \sum_{h_{M-1}=0}^{N_{M-1}} P_{h_1 h_2 h_3 \dots (h_i = N_i) \dots h_{M-1}} \left(1 - p_{i+1} + BL_{i+1}\right), \quad i = 1,2,\dots M-2. \tag{3}$$

$$BL_{M-1} = p_{M-1}\left(1 - p_m\right) \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \dots \sum_{h_{M-2}=0}^{N_{M-2}} P_{h_1 h_2 h_3 \dots h_{M-2} (h_{M-1} = N_{M-1})} \tag{4}$$

$$ST_i = p_i \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \dots \sum_{h_{M-1}=0}^{N_{M-1}} P_{h_1 h_2 h_3 \dots (h_{i-1} = 0) \dots h_{M-1}}, \quad i = 2,3,\dots,M. \tag{5}$$

These expressions are valid for the splitting lines too, with exception of the production rate, which is a little bit different:

$$PR_i = p_i \left(1 - \sum_{h_1=0}^{N_1} \sum_{h_2=0}^{N_2} \cdots \sum_{h_{i-2}=0}^{N_{i-2}} \sum_{h_i=0}^{N_i} \cdots \sum_{h_{M-1}=0}^{N_{M-1}} P_{h_1 h_2 \dots h_{i-2} 0 h_i \dots h_{M-1}}\right) \tag{6}$$

where $i \in \{S + R_1, S + R_1 + R_2, \ldots, M\}$, $S$ is the number of machines in the main branch, $R_1$ the number of machines in the first branch, $R_2$ the number of machines in the second branch and $M$ is the number of all machines in the splitting line.

## 3. The steel hull process

The theory of the finite state method will be applied to the case if a steel hull process in the shipyard Brodosplit. The workshops involved in these process are located in the department of "Brodoobrada i predmontaža", Figure 4 [6] and can be divided into 7 different workshops, namely: prefabrication line of plates (1), prefabrication line of profiles (2), plazma cutting plates (3), manual cutting and forming of profiles (4), robocuting of profiles (5), oxi cutting of plates (6) and forming of plates (7). These workshops are organized as serial and splitting lines as shown in figure 5 [7].

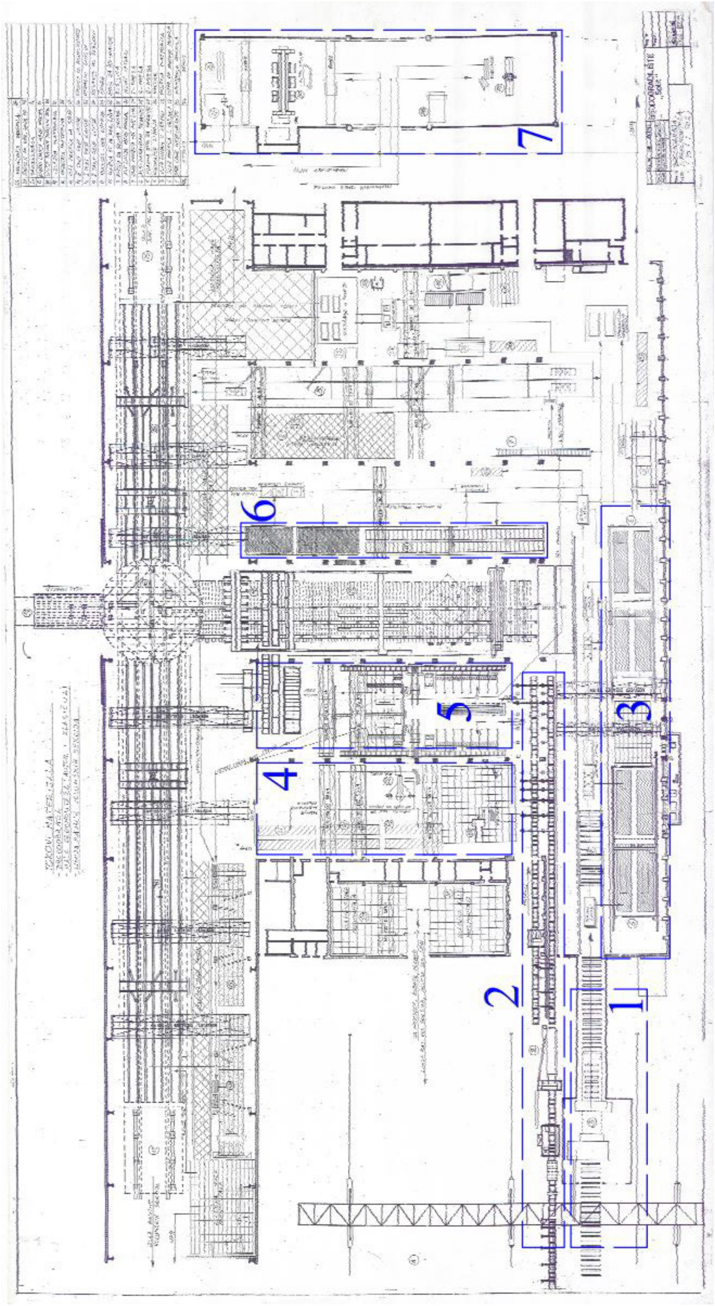


*Figure 4: The steel hull process workshops [6]*

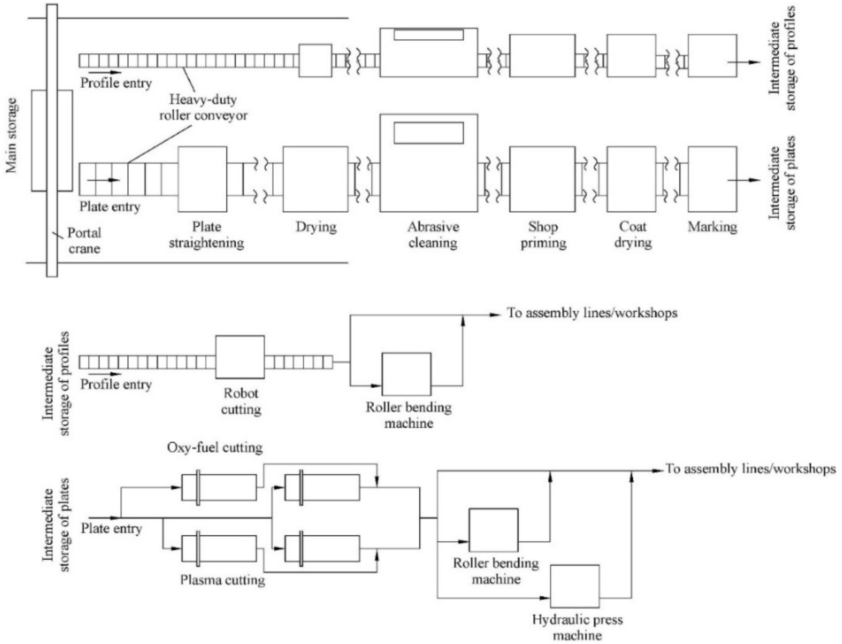


*Figure 5: The scheme behind the workshops of the steel hull process [7]*

Based on these schemes eight finite state models can be defined, Figure 6. Models A1 and B1 describe the prefabrication workshops for plates and profiles, Models A2 and B2 the fabrication workshops for plates and profiles.

The dashed circles and rectangles in Figure 6 describe virtual machines and buffers which are needed to get the models work. The operational probability and the buffer capacity of these virtual machines are close to one, respectively the buffer capacity is very large, so they just simulate a branch with no further operations.

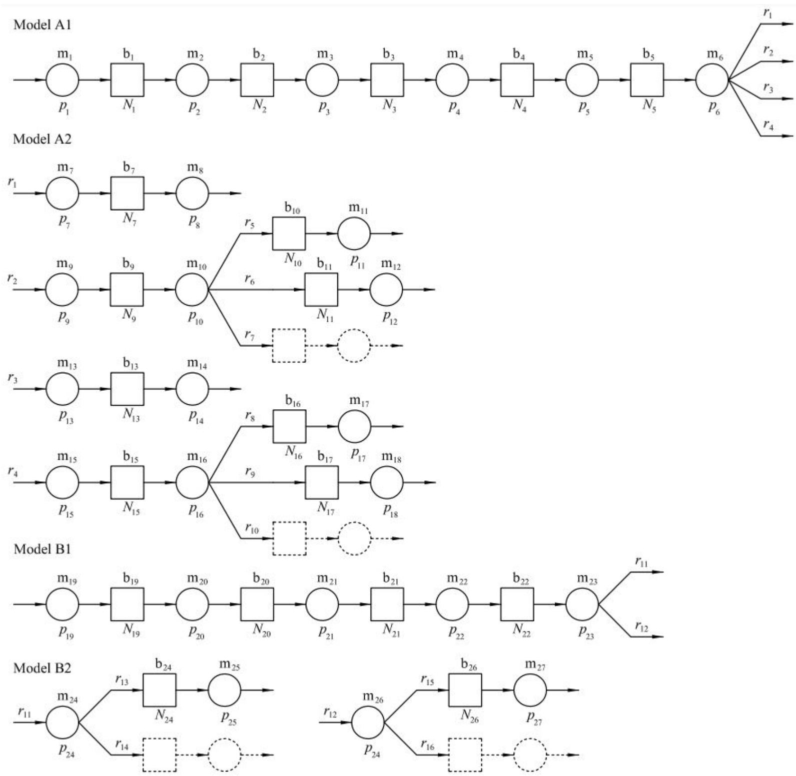


*Figure 6: Models which represent the steel hull process [6]*

To get the models run the following input data is needed: operational probability of each machine, buffer capacity of each buffer and the splitting factors for each branch which depend on the final product. The final products in this study case are one mid-ship section (section A) and one bow-section (section B) of a passenger ship, Figure 7. After the analysis of the two sections the number of models which represent the steel hull process can be reduced to five, because oxy-arc and profile robot cutting are not needed. The input data is summarized in Tables 1-3. The table 1 list all the machines' probabilities $p_i$, the real cycle time $\tau$, and the average cycle time $\tau_I$. The Table 2 list all the buffer capacities and the Table 3 shows the splitting factors. The derivation of the average cycle time as well as the calculation of the buffer capacities is shown in detail at [6].

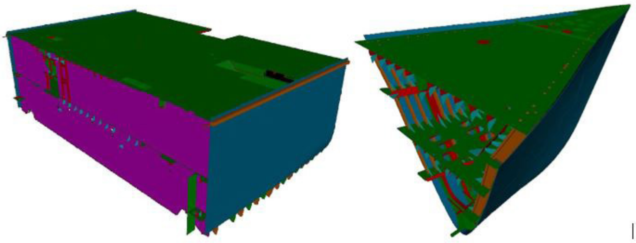

*Figure 7: Two sample sections A and B [6]*

*Table 1: List of the machines $m_i$, Operations, probabitlties $p_i$, real cycle time $\tau$*, average cycle time $\tau_I$* [6]*

| $i$ | $m_i$ | Model | Operation | $p_i$ | $\tau$* | $\tau_I$* |
|---|---|---|---|---|---|---|
| 1 | $m_1$ | A1 | Plate staightening | 0.90 | 262 | 262 |
| 2 | $m_2$ | | Drying | 0.91 | 262 | |
| 3 | $m_3$ | | Abrazsive cleaning | 0.90 | 262 | |
| 4 | $m_4$ | | Shop primer | 0.80 | 262 | |
| 5 | $m_5$ | | Coat drying | 0.91 | 262 | |
| 6 | $m_6$ | | Marking | 0.96 | 262 | |
| 7 | $m_7$ | A2 | Plasma tracing and cutting | 0.71 | 1556 | 1637 |
| 8 | $m_8$ | | Marking | 0.77 | 90 | |
| 9 | $m_9$ | | Plasma tracing and cutting | 0.71 | 1556 | 43794 |
| 10 | $m_{10}$ | | Marking | 0.77 | 1719 | |
| 11 | $m_{11}$ | | Plate forming roller bending machine | 0.44 | 3600 | |
| 12 | $m_{12}$ | | Plate forming hidraulic press | 0.44 | 5400 | |
| 13 | $m_{13}$ | | Oxy tracing and cutting | nn** | - | - |
| 14 | $m_{14}$ | | Marking | nn** | - | - |
| 15 | $m_{15}$ | | Oxy tracing and cutting | nn** | - | - |
| 16 | $m_{16}$ | | Marking | nn** | - | - |
| 17 | $m_{17}$ | | Plate forming roller bending machine | nn** | - | - |
| 18 | $m_{18}$ | | Plate forming hidraulic press | nn** | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 19 | $m_{19}$ | B1 | Drying | 0.91 | 596 | 596 |
| 20 | $m_{20}$ | | Abrazsive cleaning | 0.90 | 596 | |
| 21 | $m_{21}$ | | Shop primer | 0.80 | 596 | |
| 22 | $m_{22}$ | | Coat drying | 0.91 | 596 | |
| 23 | $m_{23}$ | | Marking | 0.96 | 596 | |
| 24 | $m_{24}$ | B2 | Oxy fuel manual cutting | 0.76 | 1200 | 2201 |
| 25 | $m_{25}$ | | Stiffner forming roller bending machine | 0.58 | 600 | |
| 26 | $m_{26}$ | | Oxy fuel manual cutting | nn** | - | - |
| 27 | $m_{27}$ | | Stiffner forming roller bending machine | nn** | - | - |

* *[sec/cycle].*
** *not necessary*

*Table 2: Buffer capacity $N_i$ [6]*

| | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ | $b_7$* | $b_9$* | $b_{10}$* | $b_{11}$* | $b_{19}$** | $b_{20}$** | $b_{21}$** | $b_{22}$** | $b_{24}$* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_i$ | 4 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 4 |

* *equivalent buffer*
** *8 profiles parallel*

*Table 3: Splitting factors according to the sample sections [6]*

| Faktor grananja | $r_1$ | $r_2$ | $r_5$ | $r_6$ | $r_7$ | $r_{11}$ | $r_{13}$ | $r_{14}$ |
|---|---|---|---|---|---|---|---|---|
| $r_i$ | 0.5 | 0.5 | 0.05 | 0.05 | 0.90 | 1 | 0.20 | 0.80 |

## 4. The simulation approach – Enterprise Dynamics

The Enterprise Dynamics software was employed to calculate the key performance indicators. This discrete event driven software offers a wide range of atoms to describe a production process. For this research the following four atoms will be enough to simulate the steel hull process for the sample sections, namely: source, server, queue and sink. The arrangement of the atoms for each model is pictured in Figure 8.

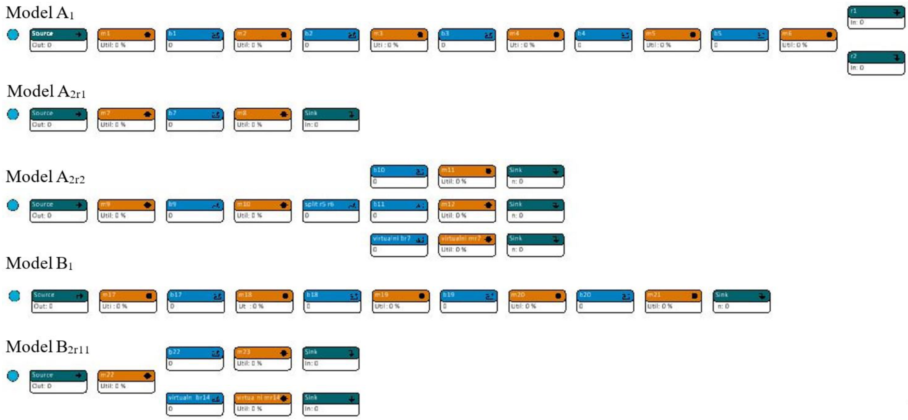


*Figure 8: Model of the steel hull process in Enterprise Dynamics [6]*

## 5. Results and discussion

The key performance indicators for the sample sections are determined by the finite state method (FSM) and the simulation approach (SIM). The results are listed in the Table 4.

The results from the FSM matches very well the results from the SIM approach except for the work in process due to the round-off errors. According to the results the production rates for the models A1 and B1 are 0,77 pieces per cycle while the probability of starvation and blockade is low, except $m_2$, $m_{19}$, $m_3$, $m_{20}$. The results of the models A2 and B2 depend on the splitting factors, so these production rates are smaller regarding to the production rate of the models A1 and B1. The higher probability of starvation can be explained due to the small number of pieces for the forming process of the profiles and plates. The work in process of the models A2 and B2 matches very well the buffer capacity, except for the buffers $b_{10}$, $b_{11}$, and $b_{24}$. Such discrepancies may implicate that the buffer capacity can be optimized.

*Table 4: Key performance indicators by the FSM and SIM approach [6]*

| | | | | | FSM* | | | | SIM** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $m_i$ | $b_i$ | $p_i$ | $N_i$ | $PR$ | $WIP_i$ | $BL_i$ | $ST_i$ | $PR$ | $WIP_i$ | $BL_i$ | $ST_i$ |
| A1 | $m_1$ | $b_1$ | 0.9 | 4 | - | 3.35 | 0.19 | - | - | 4 | 0.1 | - |
| | $m_2$ | $b_2$ | 0.91 | 1 | - | 0.93 | 0.28 | 0 | - | 1 | 0.11 | 0 |
| | $m_3$ | $b_3$ | 0.9 | 1 | - | 0.92 | 0.23 | 0.07 | - | 1 | 0.1 | 0 |
| | $m_4$ | $b_4$ | 0.8 | 1 | - | 0.81 | 0.08 | 0.07 | - | 0 | 0 | 0 |
| | $m_5$ | $b_5$ | 0.91 | 1 | - | 0.81 | 0.03 | 0.17 | - | 0 | 0 | 0.11 |
| | $m_6$ | | 0.96 | | 0.77 | - | - | 0.19 | 0.8 | - | - | 0.16 |
| A2r1 | $m_7$ | $b_7$ | 0.71 | 2 | - | 1.2 | 0.06 | - | - | 1.2 | 0 | - |
| | $m_8$ | | 0.77 | | 0.65 | - | - | 0.12 | 0.71 | - | - | 0.06 |
| A2r2 | $m_9$ | $b_9$ | 0.71 | 2 | - | 1.2 | 0.06 | - | - | 0 | 0 | - |
| | $m_{10}$ | $b_{10}$ | 0.77 | 2 | - | 0.08 | 0 | 0.12 | - | 0.01 | 0 | 0.06 |
| | $m_{11}$ | $b_{11}$ | 0.44 | 2 | 0.04 | 0.08 | - | 0.4 | 0.04 | 0.01 | - | 0.4 |
| | $m_{12}$ | | 0.44 | | 0.04 | - | - | 0.4 | 0.04 | - | - | 0.4 |
| | $r_7$ | | | | 0.64 | - | - | - | 0.64 | - | - | - |
| B1 | $m_{19}$ | $b_{19}$ | 0.91 | 1 | - | 0.93 | 0.28 | - | - | 1 | 0.11 | - |
| | $m_{20}$ | $b_{20}$ | 0.9 | 1 | - | 0.92 | 0.23 | 0.07 | - | 1 | 0.1 | 0 |
| | $m_{21}$ | $b_{21}$ | 0.8 | 1 | - | 0.81 | 0.08 | 0.07 | - | 0 | 0 | 0 |
| | $m_{22}$ | $b_{22}$ | 0.91 | 1 | - | 0.81 | 0.03 | 0.17 | - | 0 | 0 | 0.11 |
| | $m_{23}$ | | 0.96 | | 0.77 | - | - | 0.19 | 0.8 | - | - | 0.16 |
| B2 | $m_{24}$ | $b_{24}$ | 0.76 | 4 | - | 0.3 | 0 | - | - | 0.17 | 0 | - |
| | $m_{25}$ | | 0.58 | | 0.15 | - | - | 0.43 | 0.15 | - | - | 0.43 |
| | $r_{14}$ | | | | 0.61 | - | - | - | 0.61 | - | - | - |

* *Finite state Method*
** *Simulation approach*

The production time in the FSM is the product of the production rate and the average cycle time $\tau_I$,

$$T_{FSM} = PR \cdot \tau_I \,. \tag{7}$$

The production time in the simulation approach equals,

$$T_{SIM} = T_{allSIM} - T_{WPSIM} , \quad (8)$$

where $T_{allSIM}$ is the time needed for the whole simulation to produce all the pieces increased by one and $T_{WPSIM}$ the warmup time. The warmup time is the time which is measured to produce one piece. Expression (8) ensures the steady state of the production facility. At the end the production time of both approaches matches very well.

*Table 4: Production time of the steel hull process for two sample sections*

| | | A1 | $A2_{r1}$ | $A2_{r2}$ | B1 | B2 |
|---|---|---|---|---|---|---|
| $T_{FSM}$ | [h:m:s] | 7:30:39 | 27:55:02 | 685:29:08 | 4:54:54 | 148:01:57 |
| $T_{SIM}$ | | 7:16:39 | 25:37:06 | 684:35:28 | 4:45:35 | 148:15:00 |

## 6. Conclusion

The steel hull process supplies the whole shipbuilding process with the necessary steel parts. Therefore, it is important to estimate the production time of those elements to schedule all shipbuilding activities in the right time.

This research shown that the estimation of the production time for steel hull processes can be done by the recently developed finite state method. This method is easier to handle in comparison to the software tool Enterprise Dynamics and modifications of the input parameters can be done much faster.

The next step of this research would be to apply the finite state method to analyse the assembly process of steel parts into a section and later the erection process of the hull assembly. Such an approach would be the first step to a digital twin of the manufacturing process of a ship hull.

In order to estimate the impact of the assumption that the cycle time of each machine is identical, further research is mandatory by employing shipyard-floor data.

## 7. Acknowledgements

The research is supported by the Croatian Science Foundation, project UIP-2019-04-6573 ANTYARD (Advanced Methodologies for Cost Effective, Energy Efficient and Environmentally Friendly Ship Production Process Design).

We would also like to express our gratitude to Brodosplit d.o.o., for granting us the layout and data.

## 8. References


1. Hadžić, Neven: *„Ship Production I"*, Faculty of Mechanical Engineering and Naval Architecture, The University of Zagreb 2018 (in Croatian)
2. Papandopulos, Chrissoleon .T.; Li, Jingshan; O'Kelly Michael E.J.: *„A classification and review of timed Markov models of manufacturing"*, Computers & Industrial Engineering 2019
3. Ložar, Viktor; Hadžić, Neven; Opetuk, Tihomir; Slapničar, Vedran: *„Accuracy of Semi-Analytical and Numerical Approaches in the Evaluation of Serial Bernoulli Production Lines"*, Mathematics 2021.
4. Hadžić, Neven; Ložar, Viktor; Opetuk, Tihomir; Jerolim, Andrić: *„The Bernoulli splitting line: analytical and semi-analytical evaluation of the steady-state performance"*, International Journal of Production Research 2021
5. Sevast'yanov BA. *„Influence of Storage Bi Capacity on the Average Standstill Time of Production Line"*, Theory of Probability Applications 1962
6. Ložar, Viktor: *„Development of a simulation model to determine the key performance indicators of shipyard's processing lines"*, PhD Thesis, Zagreb 2023
7. Hadžić, Neven; Ložar, Viktor; Opetuk, Tihomir; Keser, Robert: *„Towards Digital Twinning of Fabrication Lines in Shipyards"*, Journal of Marine Science and Engineering 2023