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IMPROVABILITY OF THE FABRICATION LINE IN A SHIPYARD

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Summary

The ship production process is a complex manufacturing system involving numerous working stations mutually interconnected by transport devices and buffers. Such a production system can be efficiently modeled using the stochastic system approach and Markov chains. Once formulated, the mathematical model enables analysis of the governing production system properties like the production rate, work-in-process, and probabilities of machine blockage and starvation that govern the production system bottleneck identification and its continuous improvement. Although the continuous improvement of the production system is a well-known issue, it is usually based on managerial intuition or more complex discrete event simulation yielding sub-optimal results. Therefore, a semi-analytical procedure for the improvability analysis using the Markov chain framework is presented in this paper in the case of the shipyard's fabrication lines. Potential benefits for the shipyards are pointed out as the main gain of the improvability analysis.

Keywords: *Ship production process; Bernoulli production lines; Markov chains; Serial lines; Performance measures; Improvability*

1. Introduction

The ship production process is known as a perplexed, demanding, and long-lasting process composed of numerous and complex space-time interactions [1, 2]. Both space and time attributes are stochastic variables that significantly influence the productivity of shipyards, the work organization, and competitiveness in the harsh global market. Also, numerous daily shipyard-floor issues like uncertainties in material supply, production equipment failures, available personnel, or storage areas have a significant effect on production efficiency. Therefore, it is inevitable to apply advanced and rational management of the ship production process to enable and consolidate the shipyard's financial benefit, simultaneously ensuring the duly accomplishment of the contracted appointments [3].

Significant research and practical efforts have already been put into various concepts boosting efficient production at different levels. Some efforts have been focused more on practical aspects, while others addressed theoretical issues. It is well known that both approaches are of great importance and that only their successful combination yields advancement most efficiently [4-6]. However, some drawbacks like a rather time-consuming modeling relied on an experienced specialist or the lack of the observability of the results complicate their practical implementation. Also, the empirical basis of some approaches does not guaranty that the improvement is also the optimal one, particularly in cases of the most complex production processes.

The current ship production research body addresses numerous production process improvement issues. Some examples include the application of the continuous improvement method and optimized production technology resulting in the total lead time reduction [7]. Lean transformation of the built-up panel assembly in a shipyard was researched using a value stream mapping methodology to enable a significant reduction of man-hours [8]. Software techniques introducing improvements of productivity, quality, and workplace relationships into the marine industry were presented in [9]. Further possibilities of the lean manufacturing implementations were analyzed in the case of a shipyard erection block production using the product breakdown structure and group technology, [5]. A significant potential of the man-hour reduction was pointed out. A similar approach was applied in the case of stiffened steel panels of a self-unloading bulk carrier demonstrating the high potential of possible Gantt chart improvements, [6]. The possibility of the low-cost automation implementation and its effect on productivity, quality, and operational cost reduction were presented recently in [10] in cases of small and medium shipyards.

Another approach to the improvability of the ship production process using extensive simulations is also present in the governing literature body. Simulation of shipbuilding operation using a ProModel commercial simulator was used to evaluate the workflow scheduling and its impact on the additional project including constraints and conflicts between competing jobs, [11]. More specific ship production process analysis using Discrete Event Simulation (DES), [12], was applied in the case of the shipyard metal processing facility, where difficulties regarding model input data (workshop geometry, machine properties, buffering capacities, and business rules) and steep learning curve were discussed. A more general and ‘business style’ shipyard model was formulated later on using SimYard software, [13], and was evaluated repeatedly to obtain the best possible production schedule concerning total production expenses. Further application of the numerical analysis of ship production process considered modeling of the entire workshop using program Taylor ED based on the atomized representation of the workshop layout, [14]. This research considered the deterministic response of the modeled process to a selected production program in cases of two different scenarios. DES analysis of the robotized profile cutting line was considered in [15] using eM-Plant software including bottleneck analysis and process optimization using simultaneous modifications of the crane and cutting line properties.

Further research and development of the ship production process analysis and design techniques between 2009 and 2019 were mainly driven by the large data handling approach using different kinds of data managing models like advanced planning systems, business process management, and panel block handling taking into account the uncertain operational environment, e.g. [16-17]. Recently, a systematic approach to the management of the shipbuilding projects has been addressed in the light of its economic impacts, [18], while the importance of the data-driven performance evaluation was presented considering small and medium shipyards in [19]. Thus, modern shipyards rely to a great extent on the application of different integrated software solutions labeled conceptually as Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP), Computer Integrated Manufacturing (CIM), and others, striving toward integration within even broader concepts like the Digital Twinning (DT) and the Internet of Things (IoT) [20]. Such software solutions play a significant role in the complex data management relating digital ship model with many different working stations, continuously updatable databases, and graphical user interfaces providing, in such a way, simpler and more accurate ship design at different development stages. At the same time, rational material flow planning, ship equipment acquisition, workflow breakdown and planning, as well as resources and working hours monitoring is enabled. However, such software solutions usually consider a shipyard's production lines as a deterministic system which inevitably affects the evaluation of the ship production dynamics, and the expected costs and profits.

It is, therefore, the purpose of this paper to illustrate a different approach to the improvability of the ship production process following the principles of the production system engineering. The authors believe that such an approach can be effectively combined with the existing lean transformation techniques. This combination has a great potential of yielding financial benefits for the shipyard via increased production effectiveness.

The remainder of the paper is structured as follows. The next section briefly outlines the performance measures of the serial Bernoulli production lines. The efficient evaluation of the performance measures enabling the improvability analysis of the production lines is presented in the third section. The outlined approach is illustrated in one application case in Section 4, while the concluding section summarises the most important results of the research.

2. Performance measures

The performance measures have a significant role in the improvability of the production systems, [21]. A set of the fundamental performance measures comprises the production rate (PR), the work-in-process (WIP) contained at each buffer, the probabilities of machine blockage (BL), and starvation (ST) in the case of each of the considered machines. Fundamental performance measures can be used to evaluate the throughput (TP) of the production system, the number of parts at the finished goods inventory (FGI), the residence time (RT), or due-time performance (DTP). Along with that, the performance measures, particularly the probabilities of machine blockage and starvation play a critical role in bottleneck analysis and the design of lean production lines.

To illustrate the performance measures evaluation consider a serial production line composed of M machines m_i, i=1, 2, …, M of the Bernoulli(p_i) reliability model, where p_i is the probability of machine being in state {up}, Figure 1. Also, consider a series of buffers b_i, i=1, 2, …, M-1 of capacity $N_i \in \mathbb{N}^0$. Each buffer is placed in between two adjacent machines. Also, assume that (a) the machine status does not depend on the status of other machines, (b) the time axis is slotted and machines begin operations at the beginning of each slot, (c) machines' and buffers' status is determined at the beginning of each slot, (d) the machines have an identical cycle time and (e) the first machine is never starved and the last one is never blocked. Such a line is usually referred to as the Bernoulli production line, [21]. Its steady-state behavior can be formulated mathematically using the stochastic processes framework as an irreducible Markov chain ower a state-space defined by the buffer occupancy, [22]. Consequently, the stationary probability distribution is equal to an eigenvector associated with the largest eigenvalue of the pertaining transition matrix, [23].

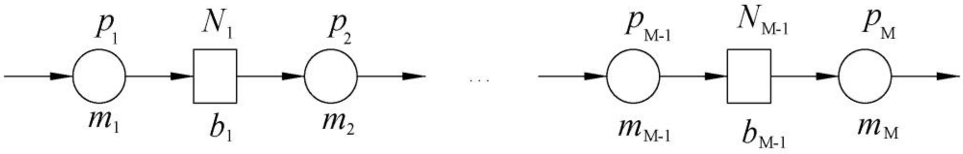

Fig. 1 A model of the serial production line including *M* machines and *M*-1 buffers

However, the complexity of the problem grows exponentially with the system's state space that makes the performance evaluation quite demanding in terms of CPU (Central Processing Unit). Hence, three different approaches to the problem have been developed namely, the asymptotic evaluation technique, [24], the simulation procedure, [15], and the analytical approach, [23]. Here, only the asymptotic evaluation technique, known also as the aggregation procedure, is presented. For more details, a reader is referred to the literature.

The asymptotic evaluation technique consists of iterative backward-forward aggregation procedures. During the backward aggregation, Figure 2a, the last two machines are taken together with the buffer between them, and a substitutional machine is formulated denoted as m_{M-1}^{b}, where b stands for 'backward'. The associated probability p_{M-1}^{b} is calculated using the analytical solution of the two machines - one buffer problem. This procedure is repeated until the whole line is aggregated into a single machine with the associated probability p_{1}^{b}.

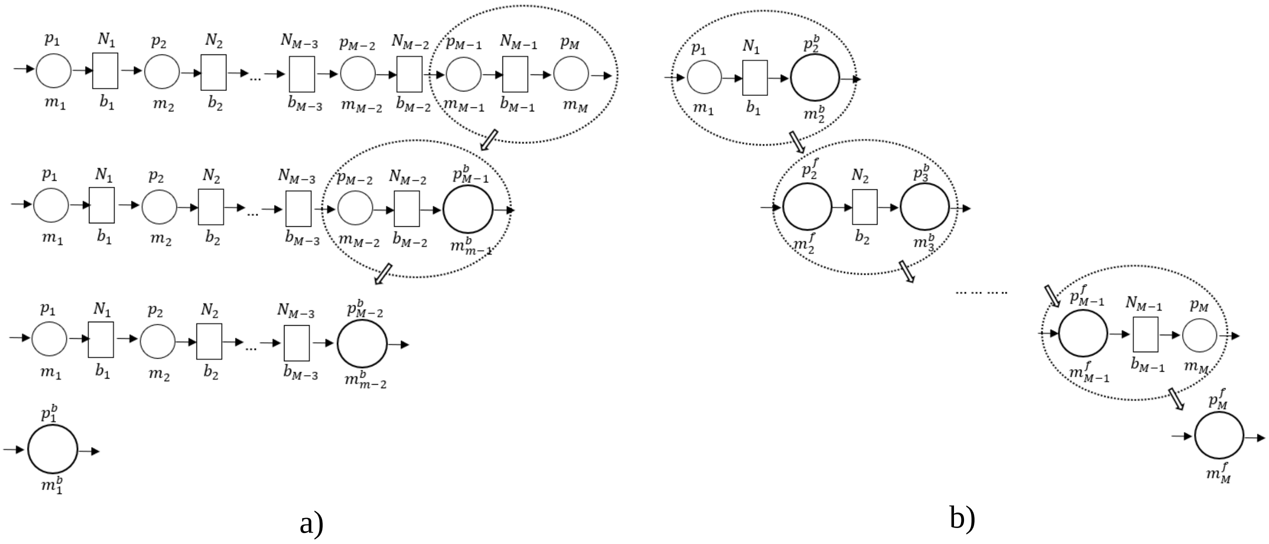

Fig. 2 Backward (a) and forward (b) aggregation, [21]

The forward aggregation, Figure 2b, begins by creating the machine m_{2}^{f}, where f stands for 'forward'. The pertaining production rate is determined using the first machine and the aggregation of the rest of the line. The forward aggregation ends with one machine, built up of the before forward-aggregated machine, the last buffer, and the last machine of the line. This procedure is repeated iteratively until satisfactory convergence is achieved.

The performance measures of an arbitrary serial Bernoulli line can be efficiently estimated using the aggregation procedure. So, here we briefly summarize their final definitions, while more details are available in [21]. Following their definitions, the *PR* is equal to,

$$PR = p_{i+1}^{b}\left[1-Q\left(p_{i}^{f}, p_{i+1}^{b}, N_{i}\right)\right],\ i=1,2,\ ...,M-1, \tag{1}$$

where

$$Q\left(p_i^f, p_{i+1}^b, N_i\right)=\begin{cases}\dfrac{\left(1-p_i^f\right)(1-\alpha)}{1-\dfrac{p_i^f}{p_{i+1}^b}\alpha^{N_i}}, \text{ if } p_i^f \neq p_{i+1}^b\\[2ex] \dfrac{1-p_i^f}{N_i+1-p_i^f}, \text{ if } p_i^f = p_{i+1}^b,\end{cases} \tag{2}$$

and

$$\alpha=\frac{p_i^f\left(1-p_{i+1}^b\right)}{p_{i+1}^b\left(1-p_i^f\right)}. \tag{3}$$

Similarly, the WIP_i at the i[th] buffer of the considered serial line is equal to

$$WIP_i=\begin{cases}\dfrac{p_i^f}{p_{i+1}^b-p_i^f\alpha^{N_i}}\left(\dfrac{1-\alpha^{N_i}}{1-\alpha}-N_i\alpha^{N_i}\right), \text{ if } p_i^f \neq p_{i+1}^b,\\[2ex] \dfrac{N_i\left(N_i+1\right)}{2\left(N_i+1-p_i^f\right)}, \text{ if } p_i^f = p_{i+1}^b,\end{cases} \tag{4}$$

where $i=1,2,\ ...,\ M-1$. The total *WIP* is equal to the sum of WIP_i at each buffer, i.e.

$$WIP=\sum_i WIP_i. \tag{5}$$

The probability of blockage of the i[th] machine, BL_i, excluding the M^{th} one, is equal to

$$BL_i=p_i\left[1-Q\left(p_{i+1}^b, p_i^f, N_i\right)\right],\ i=1,2,\ ...,\ M-1, \tag{6}$$

while

$$ST_i=p_i\left[1-Q\left(p_{i-1}^f, p_i^b, N_{i-1}\right)\right],\ i=2,3\ ...,\ M, \tag{7}$$

yields the probability of starvation of i[th] machine, ST_i, excluding the first one. The accuracy of the aggregation procedure has been proven in several research papers against results obtained using extensive numerical simulations and comparison concerning the analytical solution, [25].

Three interesting and important theoretic properties of the serial Bernoulli line are usually pointed out and exploited in the production industry. The first one is the reversibility property stating that the performance measures of the original line and its reversed version are related as

$$\begin{aligned}&PR^L=PR^{Lr},\\ &BL_i^L=ST_{(M-i+1)^r}^{Lr},\end{aligned} \tag{8}$$

where PR^L and PR^{Lr} are the production rate of the original, respectively reversed line, BL_i^L is the probability of blockage of the original line, and $ST_{(M-i+1)^r}^{Lr}$ is the probability of starvation of the reversed case. The reversibility property states that the material flow direction does not influence the performance measures of the considered production system. The second property is the monotonicity of the *PR* function. It can be shown that $PR(p_1, p_2, \ldots, p_M, N_1, N_2, \ldots, N_{M-1})$ is a strictly monotonically increasing function. The monotonicity property has some important repercussions on the differentiability of the *PR*. A detailed proof of the monotonicity property can be found in the literature, e.g. [21]. The third property, called improvability, is considered in the next chapter in more detail.

3. Improvability concepts

The term improvability is used in the literature since it cannot be expected that the rigorous optimality conditions will be met in the factory-floor conditions, mainly due to the significant randomness of the data. Two concepts of improvability have been developed so far, namely the constrained and unconstrained improvability. The constrained improvability addresses problems of the production system resource re-allocation. In the framework of the Markovian processes and the Bernoulli production lines, these resources comprise buffer capacity and an available workforce. Constrained improvability is therefore related to the optimality conditions as the unimprovable system is also an optimal one.

Governing properties of the serial Bernoulli production line are the machine reliability *Bernoulli*(p_i) and buffer capacity N_i. In case of the constrained improvability, they can be constrained as

$$p^* = \prod_{i=1}^{M} p_i, \qquad N^* = \sum_{i=1}^{M-1} N_i, \tag{9}$$

where p^* and N^* are the total available machine efficiency and the total available buffering capacity of the production system. In the first case, the system is constrained concerning the workforce (WF improvability) and in the latter considering buffering capacity (BC improvability). If both constraints are considered simultaneously, one is dealing with WF-BC improvability.

The serial Bernoulli production line is considered improvable concerning WF if a condition

$$PR\left(p'_1, p'_2, \ldots, p'_M, N_i\right) > PR\left(p_1, p_2, \ldots, p_M, N_i\right) \tag{10}$$

holds, where p'_i stands for a probability associated with the new workforce distribution. Otherwise, it is considered unimprovable, i.e. it is optimal. It can be shown that the unimprovable allocation of the workforce, p_i^*, is equal to, [21],

$$\begin{aligned} p_1^* &= \frac{N_1+1}{N_1+PR^*} PR^*, \\ p_i^* &= \frac{N_{i-1}+1}{N_{i-1}+PR^*} \frac{N_i+1}{N_i+PR^*} PR^*, \; i = 2,3,\ldots, M-1, \\ p_M^* &= \frac{N_{M-1}+1}{N_{M-1}+PR^*} PR^*, \end{aligned} \tag{11}$$

where

$$PR^* = \lim_{n\to\infty} x(n+1),$$
$$x(n+1) = \left(p^*\right)^{\frac{1}{M}} \prod_{i=1}^{M-1} \left(\frac{N_i + x(n)}{N_i + 1}\right)^{\frac{2}{M}}. \tag{12}$$

Similarly, the serial Bernoulli production line is improvable concerning WF and BC if a condition

$$\begin{aligned} &PR\left(p'_1, p'_2, ..., p'_M, N'_1, N'_2, ..., N'_{M-1}\right) \\ &\qquad > PR\left(p_1, p_2, ..., p_M, N_1, N_2, ..., N_{M-1}\right) \end{aligned} \tag{13}$$

holds, where N'_i denotes a redistributed buffering capacity. The unimprovable allocation of the governing line properties can be determined using the system of equations, [21],

$$\begin{aligned} &N_i^* = \frac{N^*}{M-1} = N_{opt},\ i = 2,3,...,\ M-1, \\ &p_1^* = p_M^* = \frac{N_{opt}+1}{N_{opt}+PR^*} PR^*, \\ &p_i^* = \left(\frac{N_{opt}+1}{N_{opt}+PR^*}\right)^2 PR^*,\ i = 2,3,...,\ M-1. \end{aligned} \tag{14}$$

Again, the unknown *PR** is determined using Eq. (12). The same production line can be improved regarding buffer capacity if a condition

$$PR\left(p_i, N'_1, N'_2, ..., N'_{M-1}\right) > PR\left(p_i, N_1, N_2, ..., N_{M-1}\right) \tag{15}$$

holds. Unfortunately, no recursive expressions yielding an unimprovable distribution of the buffering capacity can be found in the current literature body. The only approach assumes numerical experimenting. However, such an approach does not necessarily yield the unimprovable (optimal) solution necessary. Consequently, it will not be addressed further in this paper.

The unconstrained improvability deals with issues of bottlenecks identification and their removal by additional buffer resource allocation, improvement of the existing machinery, or its replacement. The concept of bottlenecks is often misinterpreted in practice. Some intuitive definitions state that the bottleneck machine is the one with the lowest p_i or the one with the largest *WIP* in front of it. However, neither of the definitions is mathematically correct. A system-based definition of the bottleneck differs between bottleneck machine and bottleneck buffer. The machine *i* is considered as a bottleneck if a condition, [21],

$$\frac{\partial PR}{\partial p_i} > \frac{\partial PR}{\partial p_j},\ i \neq j, \tag{16}$$

holds. Eq. (16) states that the bottleneck machine is the one for which the infinitesimal improvement yields the largest increase in *PR* as compared to the improvement of any other machine. Due to the monotonicity property of the production rate, both derivatives in (16) are positive. However, these partial derivatives are not available if the asymptotic evaluation technique is applied.

Nevertheless, the bottlenecks can be identified using the bottleneck indicator defined in terms of BL_i and ST_i, or the so-called arrow assignment rule. If $BL_i > ST_{i+1}$ the arrow is assigned from the machine i pointing to machine $i+1$. In the opposite case, if $BL_i < ST_{i+1}$ the arrow is assigned from the machine $i+1$ pointing to machine i. The machine with no emanating arrows is considered as a bottleneck. In the case of multiple machines with no emanating arrows, the one with the largest difference between the probability of blockage and starvations is considered as the primary bottleneck. Also, if a bottleneck machine is more often starved than blocked a buffer immediately upstream is considered as a bottleneck buffer. In a reversed case, when the bottleneck machine is more often blocked than starved, a buffer immediately downstream is the bottleneck buffer. Once identified, the bottlenecks can be removed using shipyard-floor actions like preventive maintenance, machine replacements, additional workforce assignment, or an increase in buffering capacity yielding improvements in the production rate of the serial production line.

4. Application case

The application of the outlined theory is demonstrated in the case of serial production lines of a hypothetic shipyard. Two related workshops are considered, the one including prefabrication line and the other plate cutting machines, Figure 3. Only plate fabrication will be considered here to demonstrate the applicability of the improvability concepts. Upon arrival, the material is being sorted out at the main warehouse according to its fabrication order. Usually, the storage capacity of the main warehouse is significantly larger as compared to the other storing areas inside the shipyard's warehouses. Therefore, it can be considered as an initial buffer of infinite capacity implying that the raw material is always available for production, i.e. main warehouse can never be cleared out. Although such an assumption does not reflect the reality completely it is a necessary prerequisite for the evaluation of the steady-state response of the production lines. Otherwise, one is dealing with transient problems that are out of the scope of this paper. Also, to simplify the problem additionally we will assume that the transporting devices (cranes and conveyors) are in perfect condition and are of the time-invariant reliability equal to one. Similarly, the time-invariability is assumed in the case when the reliability of machines is considered, and such data will be determined based on the overall system failure/repair intervals, while the detailed decomposition of each machine into its components and the associated reliabilities will be omitted.

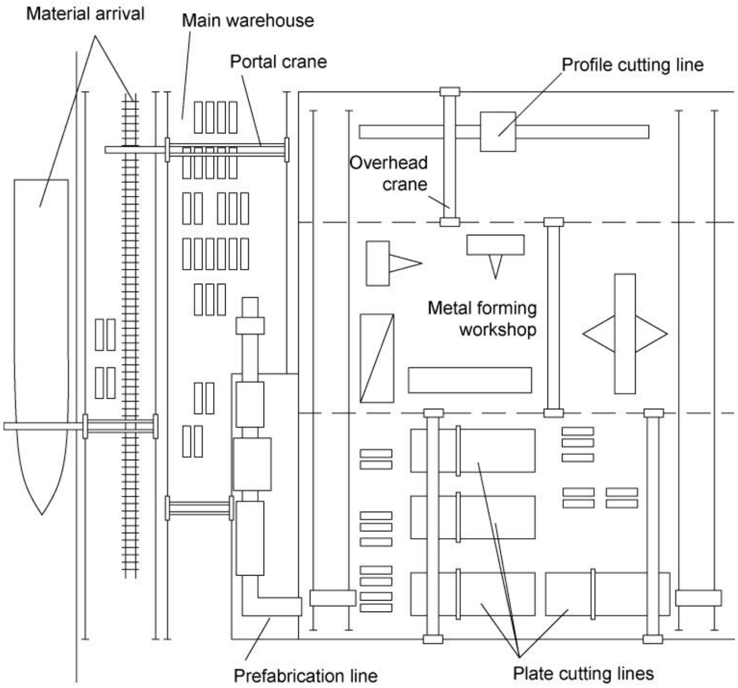

Fig. 3 Prefabrication and plate cutting lines of a hypothetic shipyard

When scheduled, the plates are placed on a heavy-duty conveyor that transports them along the plate prefabrication line composed of the plate straightening machine, drying chamber, abrasive cleaning (sandblasting) machine, and shop priming chamber, Figures 4 and 5. Apon finished prefabrication, plates are arranged at the intermediate storage area using a transverse ramp and an overhead crane. Again, when scheduled, each plate is transported using a crane to a specified cutting station. In the context of a hypothetic shipyard, Figure 6, a plate cutting workshop is composed of four cutting stations, namely the plasma cutting station, oxy-fuel station, oxy-fuel cropping station, and multi-torch oxy-fuel cutting. Therefore, each plate will continue the fabrication process at a pertaining station according to the material flow specified by the nesting documentation. When finished, the plate elements are stored at intermediate storage. From this point, they are transported to assembly stations.

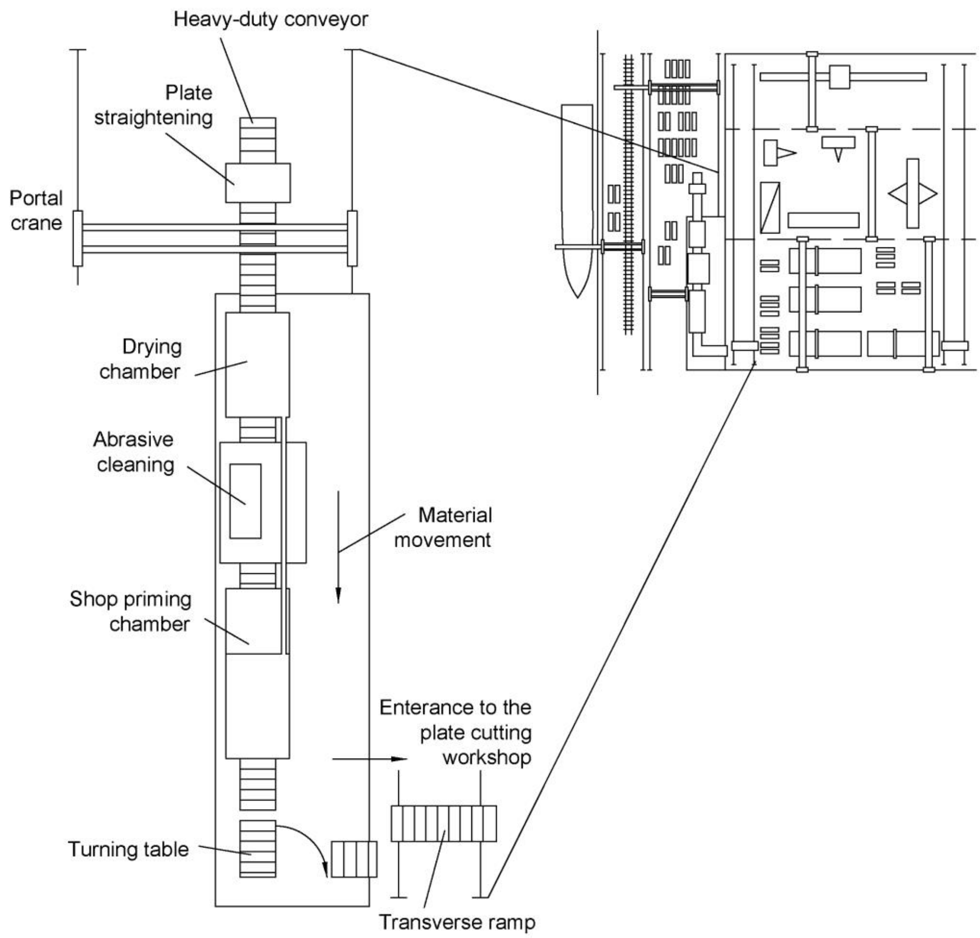

Fig. 4 Prefabrication line of a hypothetic shipyard

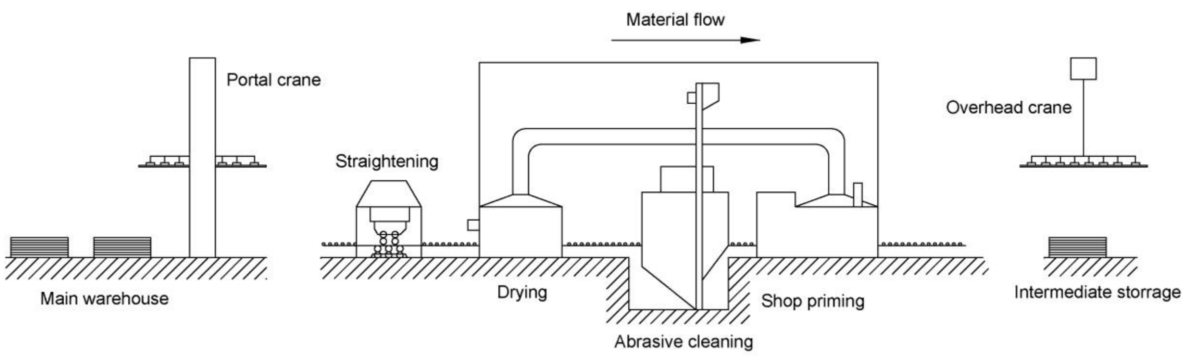

Fig. 5 Arrangement of technology operations inside of the prefabrication workshop

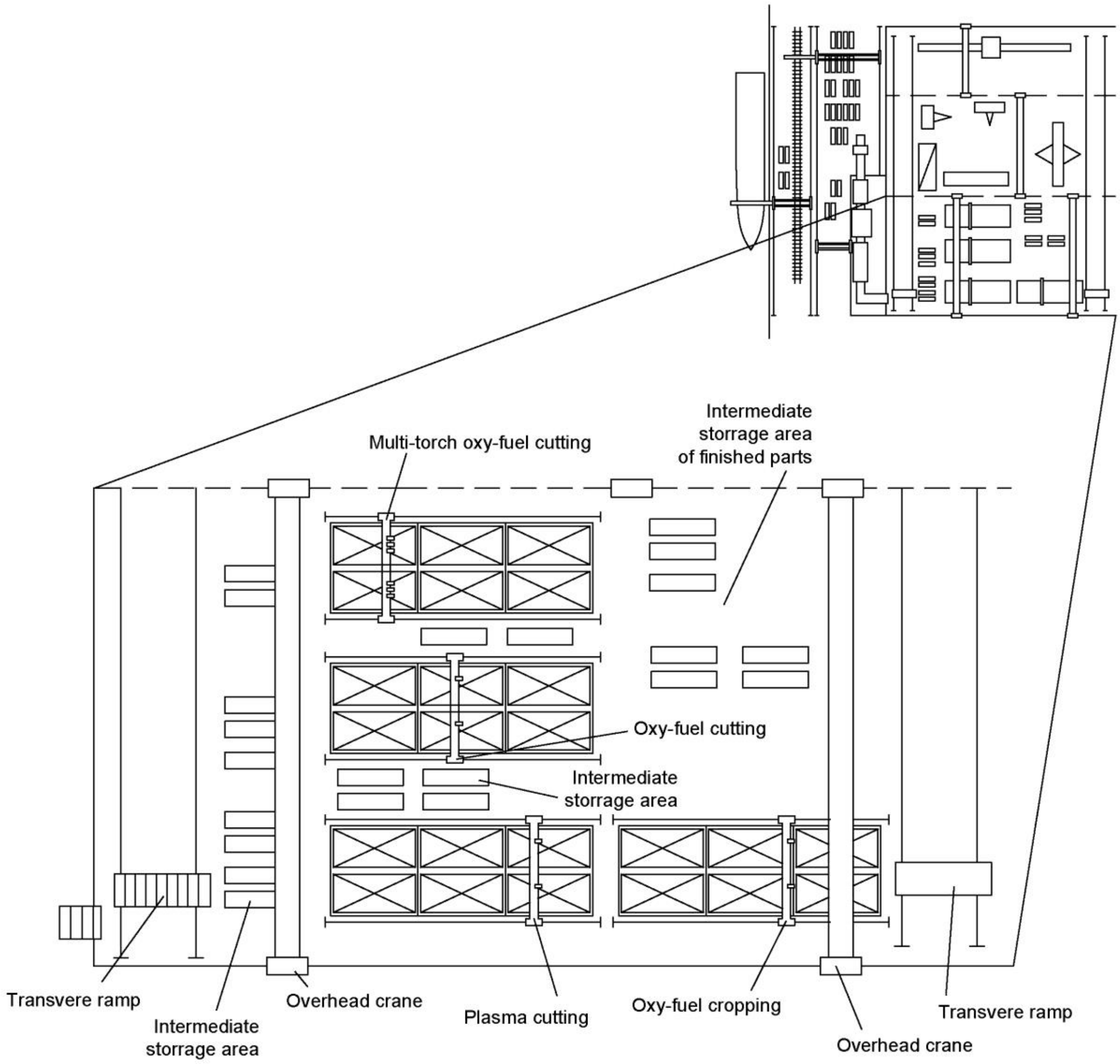

Fig. 6 Arrangement of technology operations inside of the plate cutting workshop

To model the described production process within a Markovian framework we need to consider four different production lines. Each line is composed of five working stations and four buffers that govern the stationary distributions of a pertaining Markov chain. Each line differs from others only by the reliability properties of the last machine. The remainder of the line is equal in all cases. Since the serial Bernoulli production lines are considered as a renewal stochastic process their sum yields again a Markov chain. Therefore, each line can be considered separately, while their performance measures are equal to the sum of particular events. The model of the considered production system is presented in Figure 7 and related reliability and buffering data, [23], in Tables 1-3 considering a plate of 12 m in length and 3 m in breadth. It has to be pointed out that the reliability data provided in Table 1 reflects the usual properties of the fabrication lines in a typical shipyard. However, in reality, it may differ depending on a considered shipyard and broader industrial surroundings [26].

Table 1 Declared reliability data of the production system, [26]

Operation	Straightening	Drying	Abrasive cleaning	Shop priming	Plasma cutting	Oxy-fuel cropping	Oxy-fuel cutting	Multi-torch oxy-fuel cutting
Declaration	2 plates/h	280 m^2/h	185 m^2/h	280 m^2/h	1300 mm/min	320 mm/min	300 mm/min	400 mm/min
Capacity, plate/h	2	3.88	2.6	3.88	/	/	/	/
Cycle, h/plate	0.5	0.258	0.385	0.258	/	/	/	/

Table 2 Operative reliability data and pertaining probabilities

Operation	Straightening p_1	Drying p_2	Abrasive cleaning p_3	Shop priming p_4	Plasma cutting p_5	Oxy-fuel cropping p_6	Oxy-fuel cutting p_7	Multi-torch oxy-fuel cutting p_8
Capacity, plate/h	1.8	3.54	2.3	3.45	1220 mm/min	310 mm/min	285 mm/min	360 mm/min
Probability, p_i	0.9	0.912	0.884	0.889	0.938	0.968	0.95	0.9

Table 3 Buffering data

Buffer	1	2	3	4
Length, m	20	25	25	/
N	1	2	2	30

To determine probabilities of up and down machines' periods, real machine capacities have to be determined by measurement or registered data analysis. However, as such data is not available at the moment, the assumed operative capacities of machines involved in the prefabrication and cutting lines are used, Table 2. The corresponding probabilities are determined as the ratio between operative and declared capacities. The performance measures of the considered serial lines are determined using the PSEToolbox according to the outlined asymptotic evaluation technique. A detailed introduction and user manual for the program are available in [21]. The obtained results are presented in Table 4. It can be seen that the results are almost completely the same in the considered cases. Such an effect is caused by the relatively large last buffer as compared to the other buffers. Therefore, the improvability of the production system can be performed on only one of the considered lines with effects on the complete production system. Hence, only the line with a multi-torch oxy-fuel cutting machine will be considered since it has the lowest reliability as compared to other cutting machines.

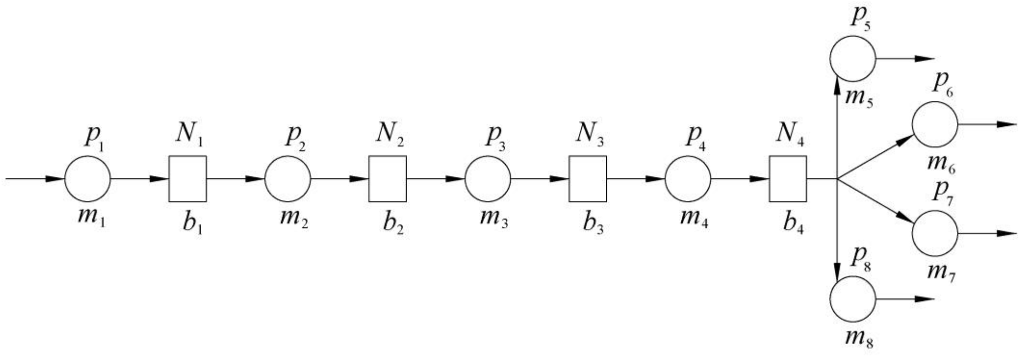

Fig. 7 Mathematical model of the considered production system

Table 4 Performance measures of the considered production lines

Last machine	i	1	2	3	4	5
Plasma cutting p_5	PR	0.872				
	WIP_i	0.91	1.34	1.18	1.09	
	BL_i	0.118	0.056	0.030	0	/
	ST_i	/	0.079	0.075	0.107	0.156
Oxy-fuel cropping p_6	PR	0.782				
	WIP_i	0.91	1.34	1.18	0.92	
	BL_i	0.118	0.056	0.030	0	/
	ST_i	/	0.079	0.075	0.107	0.186
Oxy-fuel cutting p_7	PR	0.782				
	WIP_i	0.91	1.34	1.18	1.01	
	BL_i	0.118	0.056	0.03	0	/
	ST_i	/	0079	0.075	0.107	0.168
Multi-torch oxy-fuel cutting p_8	PR	0.782				
	WIP_i	0.91	1.34	1.18	1.44	
	BL_i	0.118	0.056	0.030	0	/
	ST_i	/	0.079	0.075	0.107	0.118

Since the capacity of the first, second, and third buffer is constrained by the conveyor length, a logical choice would be to consider a constrained improvability of the production line. If the total available machine efficiency is assumed to be equal to 0.95 and the total available buffering capacity amounts to 35, the unimprovable allocation of the workforce and buffering capacity (Figure 8) yields a production rate of 0.883. Therefore, a significant improvement of almost 13% can be achieved. However, a requirement for additional buffering capacity along heavy-duty rollers can be noticed that could cause significant investments.

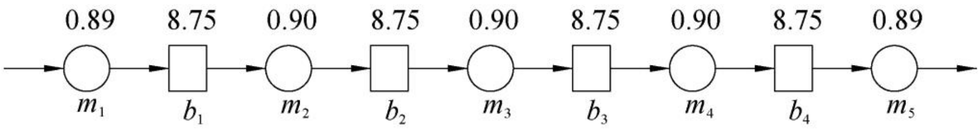

Fig. 8 Uniprovable distribution of the workforce and buffering capacity

If the same system is considered unconstrained, neither by the workforce nor by the total buffering capacity, an unconstrained improvability analysis can be performed through bottleneck identification. Again, the same system is considered using PSEToolbox, and the obtained results are presented in Figure 9. It can be noticed that the second machine is the bottleneck machine while the first buffer is considered as the bottleneck buffer.

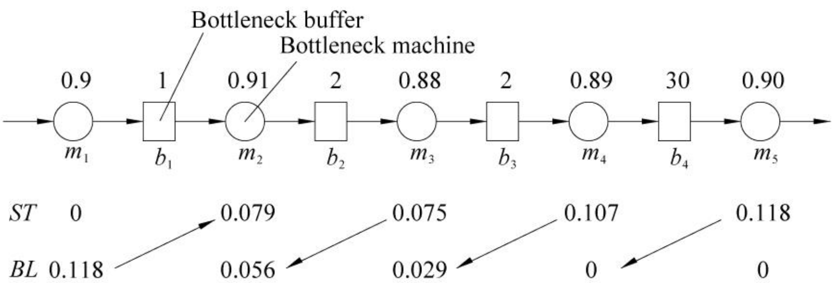

Fig. 9 Identification of bottlenecks of the considered production system

The presented and applied approach to modeling and design of the ship production process is based on the semi-analytical expressions suitable for quick and simple analysis of the systems at hand. It enables the identification of the parameters governing the performance measures evaluation. Consequently, such an approach can be used by a shipyard to improve the existing maintenance policies as well as to redistribute and enhance the exploitation of the existing workforce and storage capacities.

5. Conclusion

The ship production process is a complex system composed of numerous different and overlapping technological and transportation activities. It is of great significance to continuously consider various possible improvements boosting the shipyard's productivity and competence level. Different improvability techniques were notified in this paper namely, the lean transformation of a shipyard, numerical simulation approach, asymptotic evaluation technique, and analytical modeling. The performance measures like the production rate, the work-in-process, and the probabilities of blockage and starvation of the production system can be efficiently evaluated using the asymptotic technique, also known as the aggregation procedure. This concept was presented in the context of the Markovian framework and the Bernoulli serial production line. The obtained performance measures can be further exploited to perform the improvability analysis using the constrained and unconstrained improvability approach.

The outlined theory was illustrated in the case of plate prefabrication and cutting lines of a hypothetic shipyard. The simplicity of the approach was pointed out and a significant improvement in the production rate was achieved by the improvability analysis. Also, the bottleneck analysis was used to identify the bottleneck machine and the bottleneck buffer that will enable further improvement of the shipyard's maintenance policy. Therefore, it can be concluded that the outlined method has a great potential to be applied in the case of a real shipyard particularly if the steady-state, or long-term properties of the fabrication line are of interest. For that purpose, an additional extension of the model taking into account the reliability of the transportation devices may be required. In such a way, bottleneck identification, as well as potential improvements, can be detected and recommended having the potential to boost the overall production output.

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