

Reducing The Costs of Producing Individual Composite Molds While Simultaneously Improving Their Quality*

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Abstract

This article presents the process of producing composite molds in a small enterprise (<50 employees). The motive of the research was to improve production and product quality while reducing production costs. For optimization purposes, a very popular KPI was used: OLE (Overall Labor Effectiveness), which assesses the overall efficiency of human work. Using the OLE index, the efficiency of the production process was assessed and beneficial changes were made in four main subprocesses: waxing, gelcoat spraying, laminating, and finishing. Before optimization, the total OLE index for these processes was only 20.39%, indicating that the production process was suboptimal. After the changes, primarily the improvement of workstations, reduced transport and waiting times and influenced the OLE index, which increased to 35.27%. Composites are used as structural materials in many fields of technology. Currently, composite materials can be found in all technologies, from inexpensive structural materials used in construction, to materials for the construction of transportation vehicles, to implants used in medicine.

keywords: manufacturing costs, economic factors, composites

Introduction

Reducing the cost of manufacturing composite molds is an important factor in the production of final products. This is addressed in the works of Chen, Kuo Hattum, Sudbury, and others [1-4]. One of the most frequently used philosophies for process optimization is Kaizen/Lean. Lean Manufacturing is used in production, a field presented as "lean production" as a way to continuously eliminate waste – including time, labor, energy, processes, and investments that do not add value to manufactured products from the customer's perspective.

The term Lean Manufacturing was coined in Boston by scientists from the Institute of Technology. The term first appeared in the book by Jones D.T. and Womack J.P. entitled "The Machine That Changed the World" [5].

Implementing the Lean concept brings the following benefits: cost reduction, improved quality of manufactured products, reduced inventory, reduced space requirements, increased productivity, reduced order lead times, and increased IT system security.

Composites are materials with a heterogeneous structure, consisting of two or more components with different properties. The definition by Broutman and Krock [6] is very often used, which consists of four points:

1. A composite is an artificially produced material.

2. A composite must consist of At least two chemically different materials with a distinct separation between the components.
3. The components characterize a composite by their volumetric fractions.
4. A composite is characterized by properties that the components do not possess individually.

Most often, one of the components is a binder, which ensures cohesion, elasticity, and hardness in the material. The second component assumes structural properties that provide resistance to tension and/or compression.

According to Bieniaś [7] in composites, particles or fibers act as reinforcement. Reinforcing particles are chemical compounds of various oxides, carbides, graphite, etc. As a rule, the particle size ranges from a few to several hundred micrometers. In a volumetric system, the particles constitute 25%, and in some composites, even up to 60%. Fibers such as ceramic, plastic, or metal fibers are used in composites. These fibers have a cross-section of around 100 μm . Their percentage oscillates around 60%.

Division of composites

According to Ashby [8] currently, composites on the market are divided according to the type of matrix:

- Metal matrix – various types of alloys (iron, nickel), non-ferrous alloys (aluminum, copper, magnesium, tin, silver, lead, titanium), superalloys, and intermetallics (NiAl, TiAl, Ni₃Al, Ti₃Al, MoSi₂). The matrix of composite materials is currently based on alloys used in mass production, which guarantee appropriate technological, operational, and strength properties.
- Ceramic matrix - technical ceramics - mainly Al₂O₃ and silicon nitride Si₃N₄, glass and glass-ceramic materials (e.g., the (Al₂O₃-SiO₂-LiO₂) system), as well as carbon.
- Polymer matrix - thermosetting resins: aminoplasts, phenolic resins, chemically curable resins: polyester, epoxy, silicone, thermoplastics: polypropylene, polyamides, polycarbonate and thermoplastic polyesters, as well as, in small quantities, styrene polymers.

Description of the production process for the production of composite molds in piece production in the shipbuilding industry

The production process of polymer composites using a binder such as a chemically curable resin typically occurs simultaneously with the product's molding. The components that comprise the laminate are joined together in the mold in which the product is manufactured. After the resin cures, the finished product is removed from the mold, which may or may not require only finishing operations (varnishing, trimming). One of the fundamental elements in the composite manufacturing process is the mold, which serves as a negative reflection of the desired shape. The final product's quality and precision depend on its production. Precise mold design significantly minimizes material losses during the production process and optimizes production time.

According to Czarnecka-Banaś [9] the basic criterion for classifying molds for composite production is the type of material from which they are constructed. The type of construction depends on the selected raw materials. Many molds are made from polymer composites, allowing them to be manufactured in any desired shape. Another material used is sheet metal, from which forms of very simple structure and flat shape are made.

Optimization of the selected production process based on the principle of continuous improvement

Currently, rapidly evolving production technologies are forcing companies to seek ways to optimize their processes. The most frequently optimized processes include improving the quality of manufactured products, reducing production costs, and reducing downtime and changeover times for machinery and equipment.

The company under study manufactures composite molds domestically. It employs just under 50 people in Poland. The plant comprises the following departments: design, modeling, quality control, office, and logistics.




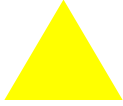
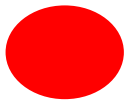

The production process for the company's main product, the composite mold, was selected for optimization. This process begins with preliminary planning of lamination and related activities. The first step was to collect relevant information on the production process and data on the times of the activities. Physical observations of production were conducted over a two-month period using the relevant worksheets presented in Table 1.

Table 1. Production time monitoring sheet

Start date and time:						
Finish date and time:						
Part number :						
Nr.	Activity	Time duration	Number of persons	Department	Supervisor	Comments
1						

The next step was to visualize the observed production process. The visualized process is presented in Figure 1, using the developed symbology presented in Table 2.

Table 2. Symbols developed to visualize the process

Symbol name	Symbol	Symbol name	Symbol
Process beginning		Parallelism	
Activity		Subprocess	
Process end		Summary	

The production process description for hand lamination consists of three main processes: waxing, gelcoat application, and resin infiltration with mats. Each process is assigned several subprocesses that are essential for the production of the composite mold. The process includes actual subprocesses identified during observations, which may differ slightly from the technological standard. These processes are performed by core employees from the laminates department, as well as the department manager and production manager (Fig. 1).

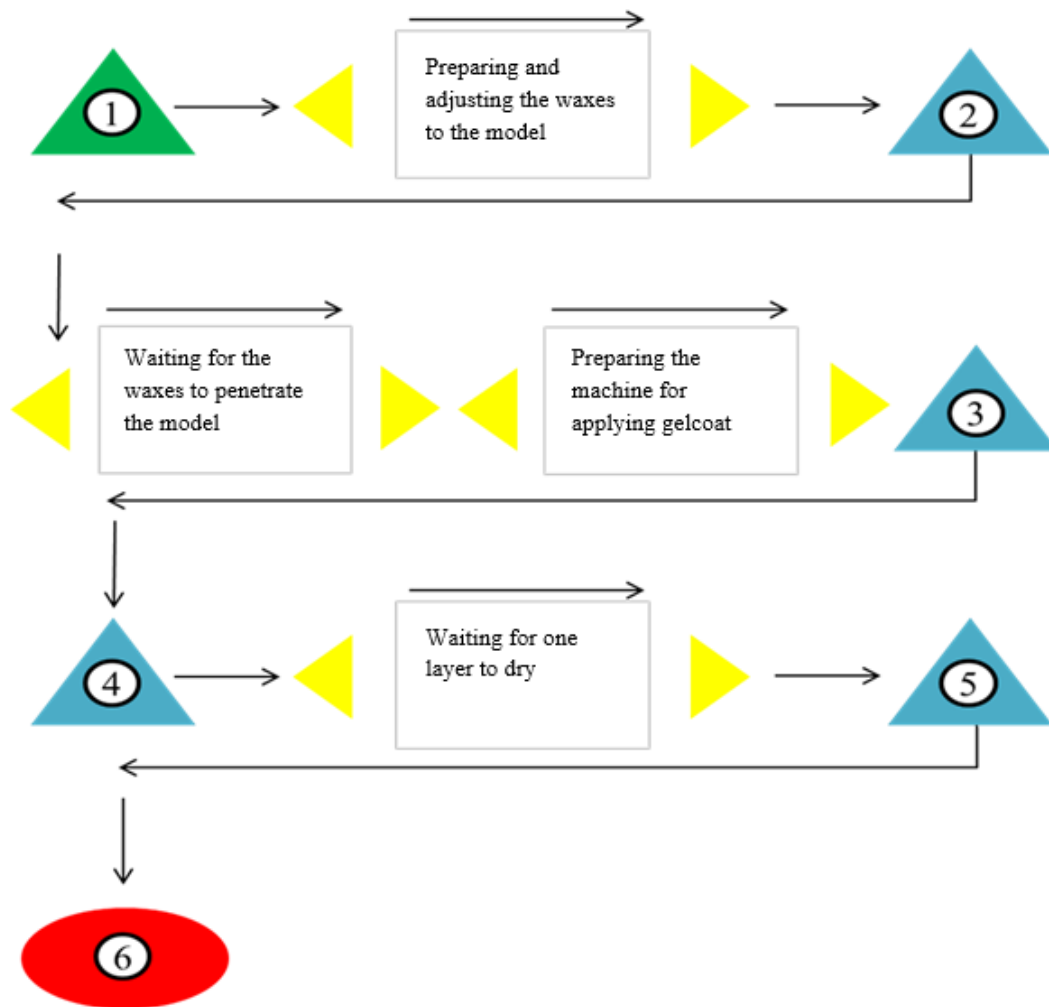





Fig. 1. Diagram of the discussed production process

1. Process observation – physical observation of all processes, sub-processes, and activities related to the production of the composite mold.
2. Applying waxes to the model – Liquid waxes are applied in six layers over two days. On the first day, three layers are applied at a minimum interval of approximately 20 minutes. The next day, three more layers are applied at the same intervals.
3. Applying the gelcoat – The gelcoat is applied 24 hours after the last wax layer. The gelcoat is sprayed onto the model in two layers. It is important to maintain the appropriate temperature during spraying. The ambient temperature should be at least 20°C.
4. Applying the first layer of vinylester mats. Maintaining the required time is crucial, as the first layer of vinylester must be applied to the gelcoat within 10 hours of spraying the gelcoat. The resin to hardener ratio is 99% gelcoat and 1% hardener.
5. Infiltration of subsequent layers occurs after the first vinyl ester layer has dried after just 24 hours. Next, the structural polyester layers are applied in a resin-to-hardener ratio of 98% resin and 2% hardener.

A load analysis was used to study the process, separating the activities into groups that add value to the process and those that do not. Each sub-process has a specific duration, allowing for the analysis of the total process time. The symbols presented in Table 3 were used to define added and non-added values.

Table 3. Symbols used to define added and non-added values

Symbol name	Symbol	Details
WD- Added Value		The activity that is most desired.
NAV- Non Added Value		The activity does not bring value but is also needed in the process.
WV- Waste of Value		An activity that should be minimized and eliminated

The AV (Added Value) group includes activities that contribute to value creation and are included in the technological process standard.

The NAV (No Added Value) group includes activities that do not generate added value but cannot be excluded from production due to technological reasons. These include activities such as drying, inspection, evaporation, etc.

The WV (Waste of Value) group includes activities that, according to the Lean improvement concept, should be completely eliminated. Such activities include, for example, overproduction, unnecessary movements, complex internal transport, and unnecessary processing.

One subprocess was selected for detailed analysis, and the aforementioned symbolism was used for its detailed description. The separated subprocess includes five activities from the AV group. These include, among others, all activities necessary to produce a mold. The layout of all elements is shown in Figure 2 and Table 4.

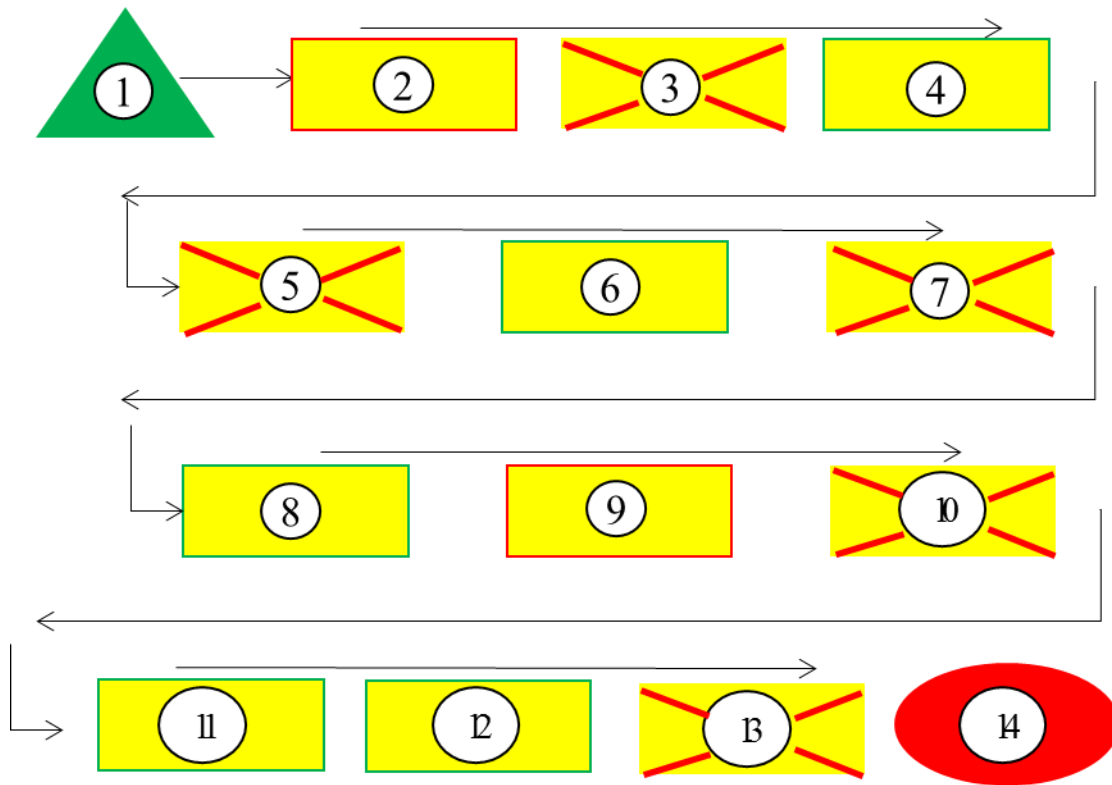


Fig.2 Example of a subprocess divided into categories.

Table 4. Subprocess flow

No.	Description
1	Beginning of the sub-process
2	Lamination process planning
3	Transportation to the waxing station
4	Waxing
5	Transportation to the gelcoat spraying station
6	Gelcoat spraying
7	Transportation to the laminating station
8	Lamination of the first vinyl ester layer and additional polyester layers
9	Quality control
10	Flange leveling and cutting
11	Station cleaning and preparation for subsequent models
12	End of the sub-process

Activities from the NAV group also occur, but they cannot be eliminated. These typically include all lamination-related plans, as well as the control performed throughout the entire subprocess. The WV group in the process in question includes five activities related to values that are redundant in the entire process and should be eliminated.

The next step towards optimization was a time summary of this process and a full analysis, which was used to achieve overall optimization. The accumulated process times are presented in Table 5, divided into groups.

Table 5. Individual AV, NAV, and WV times for the selected process.

Activities	AV	NAV	WV	Summary
Duration time	57h35min	1h20min	3h30min	62h25min

Optimization of the obtained results

A very important factor influencing total time is the human factor, the working conditions of employees, and their environment. However, these are factors that can be addressed and actions taken to improve work efficiency while minimizing negative impacts. Depending on the type of work, factors that reduce efficiency include employee absenteeism, commuting to and from work, and troubleshooting internal problems and failures. The aim of the following studies is to present the current state of work quality and to improve processes to increase production efficiency. The process analyzed in this study is the production of a composite boat mold. The overall process is presented in Table 6, along with the individual subprocess times.

Table 6. Overall process with the individual subprocess times

Activity	Total time		
	Execution	Waiting time	Activities that do not add value
Waxing	13h	24h	36min
Gelcoat spraying	5h20min	2h30min	1h14min
Laminating	6h40min	24h	28min
Finishing	3h30min	6h	2h30min

The real-time breakdown takes into account three components: execution time, waiting time, and the time of non-value-added activities. The unit of analysis was the duration of individual activities, measured in minutes, with times rounded up to the nearest whole number of minutes. It should be noted, however, that the process in question is somewhat more complex, but for the purposes of preliminary optimization, it has been simplified somewhat. All activities were generalized for research purposes to isolate the total times of individual processes. The indicators used for the work are listed in the study of the Central Statistical Office (Study of Work Organization and Distribution in Poland in 2015). According to Parmenter D. [9] for optimization purposes, a very popular KPI was used: OLE (Overall Labor Effectiveness), which assesses the overall efficiency of human work.

The OLE indicator consists of the product of components such as availability (A), performance (P), and quality (Q). The total human labor efficiency is therefore:

$$OLE = A \cdot P \cdot Q$$

Each of the components A, P, Q, as well as the indicator itself, is expressed as a percentage ranging from 0% to 100%. The availability parameter (A) describes how much time is lost due to downtime in relation to the actual time of work performed and is described by the formula:

$$A = \frac{RT}{PPT}$$

where RT(Run Time) is the actual process execution time, which does not take into account downtime; PPT(Planned Production Time) – planned production time.

Efficiency P shows the ratio of the process execution time to the times calculated based on technological standards. This is described by the formula:

$$P = \frac{TC * ITC}{PPT}$$

where TC (Total Count) is the number of items produced; ITC (Ideal Time Cycle) is the ideal time for one cycle of the given process.

The third and final indicator is quality Q – it describes the number of items that do not meet requirements and is defined by the formula:

$$Q = \frac{GC}{TC}$$

where GC (Good Count) - number of correctly executed elements.

For the optimization, the Q factor was assumed constant because the mold-making process is too long and individual, and all repairs are performed on an ongoing basis. If a given component does not meet quality requirements, it is corrected by the people performing the process. Therefore, Q is always assumed to be 1. The number of TC components produced is set to 100.

A process that exhibits problems increases its duration, and therefore indicators such as A and P also deteriorate. Therefore, omitting the Q parameter is justified, as the OLE factor can still be calculated.

Table 6 presents the results of the OLE factor calculations for the indicated process. This table is divided into two segments: before and after optimization. The data in Table 5 and the calculations of the individual indicators were used to calculate the indicators. The results for the segment before optimization contain the results for the current state, while those for the segment after optimization show the ideal state in which all unnecessary activities performed during the production process have been removed.

Process optimization										
	Optymization before						Optymization after			
Activities	RT	PPT	A	ITC	P	OLE	<i>PPTopt</i>	<i>Aopt</i>	<i>Popt</i>	<i>OLEopt</i>
	[min]	[min]	[%]	[min]	[%]	[%]	[min]	[%]	[%]	[%]
Waxing	780	2256	34,57	1400	62,06	21,46	2133	36,57	65,64	24,00
Gelcoat spraying	320	544	58,82	300	55,15	32,44	422	75,83	71,09	53,91
Lamination	400	1100	36,36	280	25,45	9,26	700	57,14	40,00	22,86
Finishing	210	370	56,76	120	32,43	18,41	250	84,00	48,00	40,32

Summary	1710	4270	186,52	3313	175,09	81,56	3505	253,54	224,73	141,09	
Avg. value	427	1068	46,63	525	43,77	20,39	876	63,39	56,18	35,27	

David Parmenter [10] in his book "Key Performance Indicators (KPIs): Creation, Implementation, and Application" describes that the OLE value should be around 80%, but in practice, achieving this value is very difficult. However, an analysis of global manufacturing companies shows that this indicator ranges between 30% and 80%.

For the process under study, the OLE value is 20.39%. The most efficient operation to date is gelcoat spraying at 32.4%, while the least efficient is lamination at 9.26%. This low efficiency is due to the length of the process. Unfortunately, the technology cannot be accelerated, so the time between individual process steps plays a key role.

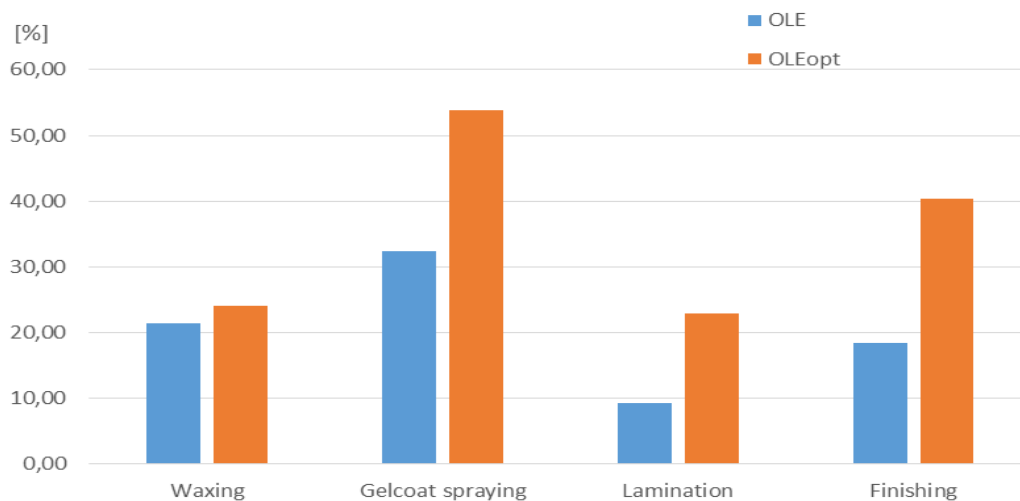


Fig. 3. The ratio of OLE indicators before and after optimization.

Figure 3 presents a comparison of OLE indicators before and after optimization. As can be seen, the operation that had the greatest impact on efficiency was finishing. Efficiency increased from 18.41% to 40.32%. The smallest changes in efficiency were observed in the waxing operation. This process prevents efficiency gains because drying and wax penetration times cannot be accelerated.

The steps taken to achieve the above-mentioned results are as follows:

- Reduction in waxing time;
- Reduction in model transport time;
- Reduction in laminating wait time;
- Reduction in finishing time.

To increase OLE indicators, waxing time was shortened by changing the method of applying wax to the model. Instead of sponges, which absorb a large amount of wax, cotton materials were used, which are more efficient at applying wax to the model. Regarding waiting times during laminating, the ambient temperature was increased by using infrared heaters. This step reduced the drying time of individual laminate layers. The reduction in finishing time was achieved through a more precise lamination process, resulting in a more efficient laminate finish, which resulted in shorter times for leveling and edge trimming of the composite. The final step, and the most important one because it significantly increased efficiency, was the reduction in transport time. The stations for individual sub-processes were modernized, allowing the model to remain in one location. Only the individual tools necessary for a given sub-process were transported.

Conclusion

This article presents the construction of composite molds from various materials and describes their production methods. Next, a detailed analysis of the composite mold production process in the production of watercraft was conducted at the selected company, and the execution times of individual subprocesses were measured. Based on the Lean Management concept and its tools, waste was categorized and identified. This allowed for optimization that could accelerate the production process. Using the OLE index, the efficiency of the production process was assessed and beneficial changes were made in four main subprocesses: waxing, gelcoat spraying, laminating, and finishing. Before optimization, the total OLE index for these processes was only 20.39%, indicating that the production process was suboptimal. After the changes, primarily the improvement of workstations, reduced transport and waiting times and influenced the OLE index, which increased to 35.27%, allowing for improvements in the composite mold production process.

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