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Modelling and Simulation Method for Production Process Automation in Steel Casting Foundry

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Abstract

The problem of production flow in steel casting foundry is analysed in this paper. Because of increased demand and market competition, a reorganisation of the foundry process is required, including the elimination of manual labour and the implementation of automation and robotisation of certain processes. The problem is how to determine the real difference in work efficiency between human workers and robots. We show an analysis of the production efficiency of steel casting foundry operated by either human operators or industrial robots. This is a problem from the field of Operations Research for which the Discrete Event Simulation (DES) method is used. Three models are developed, including the foundry before and after automation when taking into consideration parameters of the availability of machines, operators and robots. We apply the OEE (Overall Equipment Effectiveness) indicator to present how the availability, performance and quality parameters influence the foundry's productivity. In addition, stability of the simulation model was analysed. This approach allows for a better representation of real production processes and the obtained results can be used for further economic analysis.

Keywords: Automation and robotics in foundry, Transport systems in foundry, Discrete event simulation, Human factors, OEE - overall equipment effectiveness

1. Introduction

Currently, increased demand and market competition can be observed in the manufacturing industry, including the foundry sector. Thus modernisation of technical equipment and reorganisation of the production process in foundry is required in order to achieve higher production volume, flexibility of manufacturing processes and product quality. Due to the complexity of different foundry processes, the problem of production flow in a foundry is very difficult to analyse. This difficulty consists in the need to synchronise several different processes to create a flow through the plant; therefore, extensive use of computer simulation of foundry processes is observed, e.g. it can be used for robust system design of a melt facility [1], rationalisation and improvement of foundry processes [2, 3, 4] or lot sizing and scheduling of sand casting operations [5]. A comprehensive review of models and algorithms for production planning and scheduling in foundries is presented in [6]. The article discusses examples and the classification of production planning and scheduling systems in the foundry industry as described in the literature and outlines the possible directions of development of the models and algorithms used in such systems. The main conclusion is that the mathematical methods, constraint programming and other computational intelligence techniques as presented in the literature in the field of operations research and production management are generally inadequate for planning a real-life production process because of their computational complexity. These methods are in fact dedicated to solving standard problems only, whereas many real-world production planning problems require the simultaneous solving of several problems (in addition to task scheduling and lot-sizing, problems such as workforce scheduling, packing and transport issues, and machine tending arise), including problems that are difficult to structure.

Based on a review [7], the advantages and disadvantages of simulation in manufacturing are presented, gaps in current practices are identified and future trends and challenges to be met in the field are outlined.

Thus, production planning is made possible via an analysis and simulation of key production and organisation factors. The simulation model can be used to evaluate production capacity, to schedule production tasks and to detect bottlenecks limiting system performance.

In this work, the production process in a steel casting foundry is analysed. Production reorganisation shall include the elimination of manual labour and the implementation of automation and robotisation of some processes.

The main problem is how to determine the real difference in work efficiency between human workers and robots.

The methodology of the modelling and simulation process (Fig. 1) includes an analysis of the real problem, conceptual design and model synthesis, a simulation experiment and implementation of the obtained solution [8, 9].

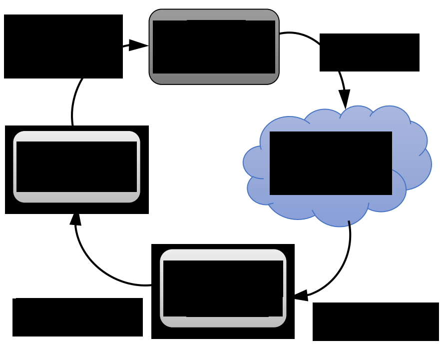

Fig. 1. Methodology of the modelling and simulation process

The aim of the current study is to develop a methodology that allows to clearly define an increase in production efficiency associated with an improvement of production systems, e.g. the replacement of human resources with industrial robots [10]. Moreover, another question is which parameters are important to evaluate this problem and involves factors related to human-machine interaction. There are some human factors that are difficult to model because of human individuality. In addition, factors related to machine parameters, machine maintenance, reliability and failures, the transportation system, storage system and quality control system should all be taken into consideration.

Therefore, we applied the OEE (Overall Equipment Effectiveness) [11] indicator to present how the availability, performance and quality parameters influence the foundry's productivity.

2. Work efficiency and OEE

There are some key performance indicators that can be used to evaluate the efficiency of production systems [12]:

- Production throughput,
- Products quality,
- Average waiting time of ready parts,
- Manufacturing lead-time (MLT),
- Queue length,
- Work in progress (WIP),
- Mean tardiness and rate of tardy parts (relative to the number of parts produced on-time),
- OEE - Overall Equipment Effectiveness.

Work efficiency and the use of means of production can be expressed by using the OEE metric, which depends on three factors: availability, performance and quality [12].

OEE = (Availability) x (Performance) x (Quality) (1)

Availability can be defined as the ratio of time the unit is being capable of doing a task in given time interval to the full length of that interval (e.g. one work shift). Availability is reduced by machine setups, disruptions at work and machine failures.

Availability=(available time - failure time)/(time interval) (2)

Performance is defined as the ratio of the time to complete a task under ideal conditions, compared to completing it in real conditions or the ratio of the products obtained in reality, to the number of possible products that can be produced under ideal conditions. Performance is reduced by loss of working speed, related with the occurrence of transport operations, human errors, etc.

Performance = (ideal cycle time)/(real cycle time) (3)

Quality is defined by the ratio of the number of satisfactory quality products in relation to the total number of obtained products.

Quality = (good products)/(overall products) (4)

The number of satisfactory quality products is a random variable which can be described by normal distribution with standard deviation sigma. Quality levels are determined for ranges of the standard deviation sigma. In traditional production systems, a level of ±3 sigma is considered to be sufficient, which means 97.3 percent of well-made products [13].

In reality, most manufacturing companies have OEE scores closer to 60%, but there are many companies with OEE scores lower than 40%, and a small number of world-class companies that have OEE scores higher than 85% [14].

In the foundry sector, the OEE value varies from ca. 45% for hand-operated foundry [15] to ca. 75%-80% for automated casting lines [16].

3. The production process in steel casting foundry

The object of the research is the production flow in small steel castings foundry, in which small-scale batch production is made to the client's order.

Currently, body castings for a family of valves are produced. A typical casting has a mass of ca. 40-100 kg and is made with the use of sand moulds.

Due to the increase in customer orders, possibilities to increase production are considered in order to meet demand and to maintain the flexibility of production. In the process production of castings, several specific operations and activities occur, inter alia, the preparation of sand, patterns, moulds and cores, preparation of the cast with the right chemical composition and melting in an electric arc furnace, splashing moulds with liquid metal, solidification of metal and cooling of the mould, casting shakeout from the mould, removal of the sprue, casting cleaning, heat treatment, quality control and others (Fig. 2).

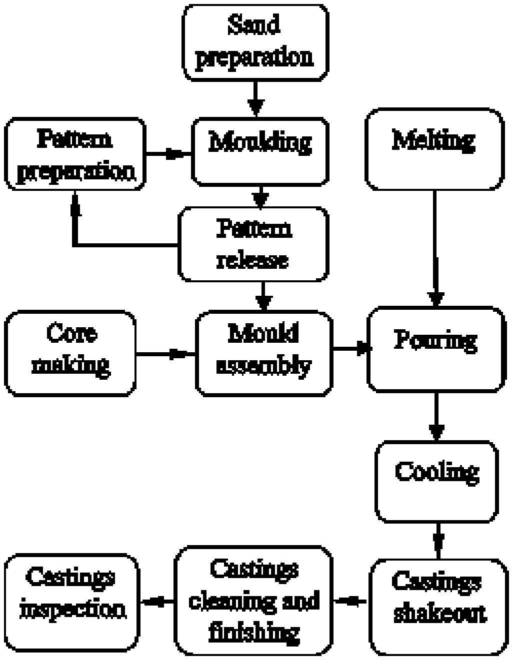

Fig. 2. Steel casting production process

Most of the work requires human operators, but due to low productivity and hazardous working conditions the trend to achieve an increasingly higher level of automation and robotisation of manufacturing processes in foundries can be observed. Automation allows for a significant increase in production efficiency as well as reliability and stability of the production system, but it also requires high investment costs.

The synchronisation of several different processes is necessary in order to obtain production flow in the foundry. Some of these processes take a very short period of time but others require a long time period of preparation.

The typical process times are presented in Table 1.

Table 1.
Typical casting process time

No.	Process stage	Process time
1	Box and pattern preparation	2 min.
2	Hand moulding	9-11 min.
3	Sand bonding	30 min
4	Pattern removing	2,5 min.
5	Pattern cleaning	2 min.
6	Mould and core assembly	4 min.
7	Melting	4-7 hours
8	Pouring	15-30 s.
9	Cooling	4-8 hours
10	Casting shakeout	2 min.
11	Visual inspection	1 min.

The production process includes the preparation of sand (from which the mould is made) based on pattern units, which are reusable but their number is limited. After the initial moulding of the two-part form, binding of sand is required which takes at least 30 minutes. After binding, the mould is disassembled and the pattern is removed, but it should be cleaned and painted before further use. Then at the next station cores are mounted inside the mould and finished moulds are reassembled. Then the moulds are transported with a crane into the pouring place. At the same time, liquid steel is prepared in the arc furnace. The main ingredients of the charge are foreign scrap steel, own circulating scrap and alloy slag forming materials, carburisers and deoxidising additives. Due to the contamination of scrap metal in the process of melting, slag removal and refining are required. The temperature and chemical composition of the cast is tested each time in order to obtain the required grade of cast steel. The entire process of melting is long and irregular, and takes approximately 4-7 hours.

Then the moulds are poured with liquid metal (by gravity) with a ladle transported using the overhead crane. Pouring is the key phase of the casting manufacturing process and must be carried out relatively quickly, because of the fast cooling rate of liquid metal. An adequate pouring speed of the mould must simultaneously be ensured. Typical pouring times are ca. 15-30 seconds depending on the mass, wall thickness and height of the casting.

Moulds flooded with liquid metal are very hot and must be left to cool to solidify the metal, which can take ca. 4-8 hours. Then the castings are shaken out of the mould. Sand is recovered and the castings are subjected to an initial visual inspection. Castings with slight defects can be repaired by welding and further treatment, while defective castings that are non-recoverable (5-10%) are scraped and will constitute a part of the next charge. Valid castings are transported to the finishing department for removal of the sprue, cleaning, heat treatment, and final quality control. Cleaned and checked castings are finally sent to the recipient.

4. Modelling of steel casting foundry

FlexSim 2016 software was used to build the foundry model. In the first stage, a simple reference model was created, as presented in Figure 3.

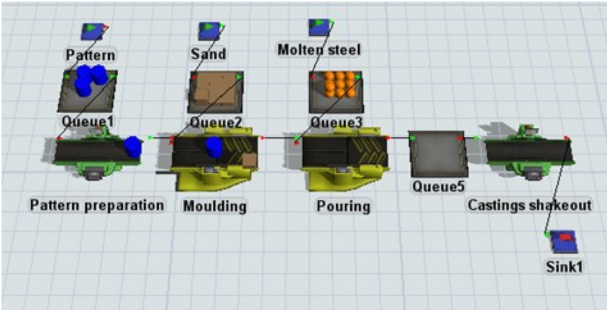

Fig. 3. Simplified model of steel casting foundry

This simplified model includes only basic processes and represents the production flow in ideal conditions. It shows that the moulding station is the bottleneck for production flow. In the next steps this model was expanded with handling and transport processes, including human operators and a crane. A detailed model of foundry is presented in Figure 4. This model includes all of the stations from one casting department of foundry.

According to the assumed methodology, the model includes time schedules that define the availability of machines and operators, e.g. an operator's schedule for one shift includes 10 minutes for work preparation at the beginning, 15 minutes for a break and 5 minutes to clean the workstation at the end of the shift. Another schedule defines the time to pour a batch of moulds once a shift. There is a long delay time in the cooling process of the hot mould before casting shakeout, which means that the castings are obtained in the next shift; therefore, a warmup period in the simulation is required to obtain the required production performance.

After visual inspection, good products are sent to other departments for machining and heat treatment, and poor products are scraped and resent to be remelted.

The simulation experiments show that production of 30 castings per one shift is possible, which is consistent with the actual production process.

Some scenarios of foundry reorganisation were taken into account, e.g. the simple addition of another moulding station with operators does not give a satisfactory increase in production volume, and only the implementation of an automated production line with a horizontal moulding machine, a core assembly robot and a pouring robot gives an appropriately high production increase. The model of the automated line is presented in Figure 5.

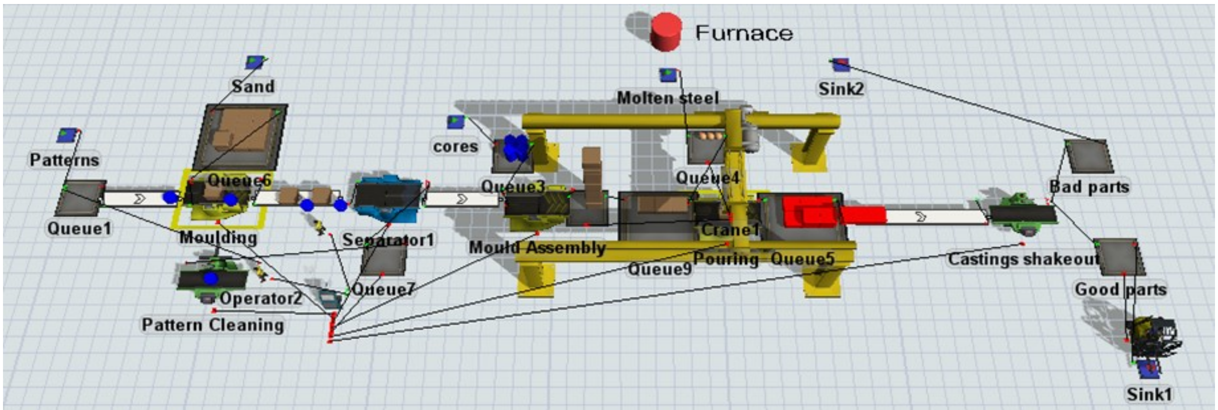

Fig. 4. Model of a hand operated foundry

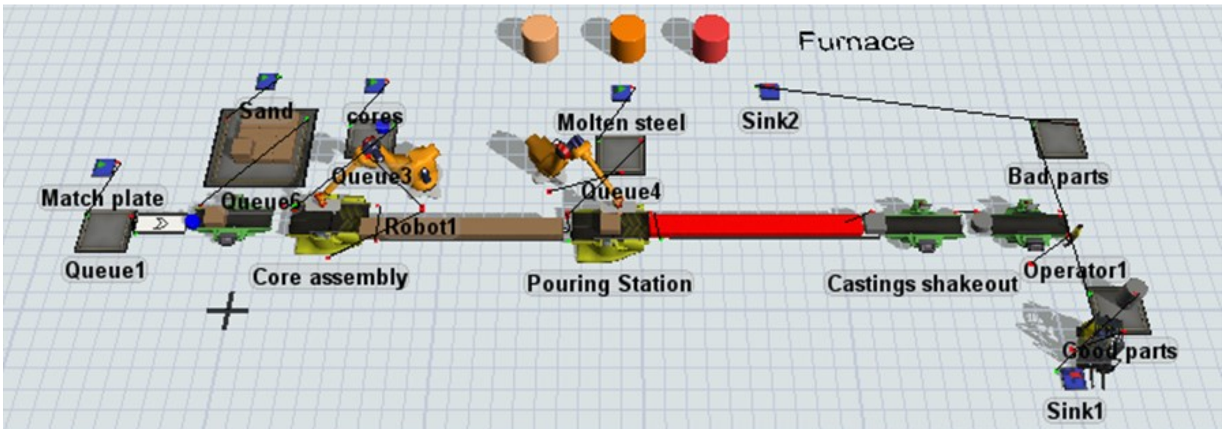

Fig. 5. Model of an automated foundry

An automated horizontal no-flask moulding machine allows for the production of ca. 60 moulds per hour. Additional furnaces are required for continuous delivery of the liquid metal to ensure continuous production of castings. In this case another bottleneck can occur in the pouring station; therefore, an industrial robot should be used for pouring operation to provide high production performance.

The use of an automated line will improve production throughput and OEE indicators, and availability, performance and product quality should be much better than those obtained from handmade moulds. The time schedule includes a changeover of the whole line once per shift; with the help of the SMED method this should take no more than 15 minutes.

The question is how large the real difference will be in work efficiency between a human operated foundry and an automated foundry line? The results of the simulation experiments that provide the answer to this question are presented in the next section.

5. Simulation experiment results

In order to compare two different models of a foundry, a simulation run time of 24 hours was assumed with a warmup period of one 8-hour shift. Because of the stochastic parameters of some of the objects in the model, one simulation run does not give a complete picture of the problem; therefore, a series of 30 simulation experiments were performed. Reliability parameters and failures were omitted due to a lack of data.

Because the presented model was built based on OEE indicators, including availability, performance and quality parameters, the obtained simulation value of production can be used directly to calculate the OEE value in relation to the production limit value from the reference model, which simulates ideal production conditions for all available time (Eq. 5).

$$OEE = P_{avg} / P_{lim} \quad (5)$$

Where:
P_{avg} – average production value of good quality products,
P_{lim} – production limit value from the reference model.

The experiments results are collected in Table 2.

Table 2.
Results of simulation experiments - average production value P_{avg} for 30 simulation runs with a confidence level at 90%.

	Hand operated foundry	Automated foundry
Simulation time [hours]	(8) + 24	(8) + 24
Average production Pavg [Pcs.]	80.7	1354.4
Production limit [Pcs.]	143	1726
Standard deviation [Pcs.]	2.67	5.5
OEE	**0.564**	**0.784**
error	±0.006	±0.002

The obtained result shows much greater production throughput for an automated foundry, i.e. ca. 12 times greater than for a hand operated foundry.

Figures 6 and 7 show the box and whisker plot of a well-made product replication for each simulation run, for a hand operated foundry (Fig. 6) and an automated foundry (Fig. 7).

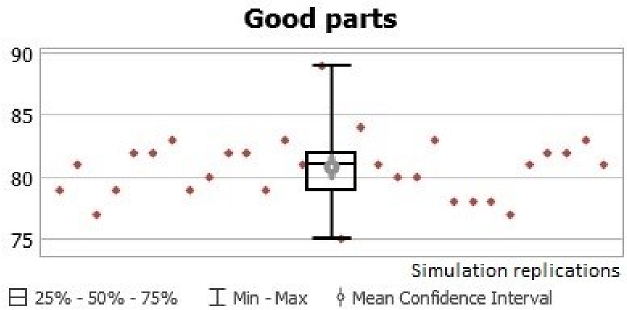

Fig. 6. Production value replication chart for a hand operated foundry

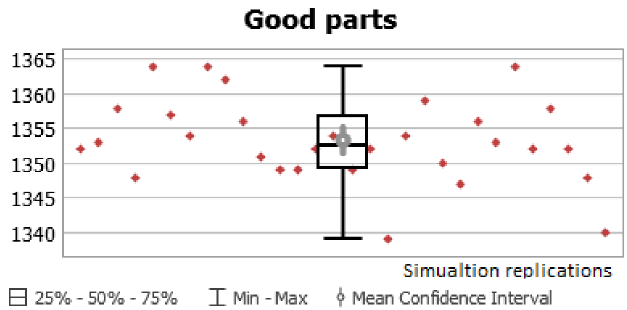

Fig. 7. Production value replication chart for an automated foundry

The standard deviation and dispersion of production value is greater for the automated foundry because of a much greater production volume. The relative range of dispersion is ca. 17% for the hand operated foundry and 1.8% for the automated foundry. The model of the automated foundry is also more stable in the long time simulation.

The obtained OEE values are consistent with the assumptions and other calculations of the OEE indicators, as shown in Table 3.

Table 3.
Comparison of OEE indicators

	Hand-made	Automated
Availability	0.9375	0.9688
Performance	0.666	0.8333
Quality	0.90	0.97
OEE	0.562	0.783

Production flow depends on timely delivery and machine reliability; therefore, in the next research study also machine and human reliability should be taken into consideration as these can have a significant effect on long time simulation.

6. Conclusions

As was expected, the simulation experiments confirm the advantage of applying an automated foundry as compared to a manually operated one. This is one of the best examples of robotic improvement in industry. However, in other cases, the difference between a human operator and industrial robot is not as clearly visible.

The computer simulation of the detailed model of the steel casting foundry, with machines, industrial robots and human resources, allows for a better representation and understanding of a real production process. This is particularly visible in the case of work in three shifts per day for a long-time period. Work organisation and synchronisation play a key role, therefore the efficiency of the production line operated by robots has improved the OEE indicator by 22 percentage points as compared to a manually operated foundry.

The use of the OEE indicator allows to compare results from other production systems. In the foundry sector, the OEE value varies from ca. 45% for hand-operated foundry to ca. 75%-80% for automated casting lines. In reality, there are and a small number of world-class companies that have OEE scores higher than 80%. Thus, there are some areas for improvement of availability, performance and quality. Availability depends on planned and unplanned breaks at work. The performance score decreases due to loss of working speed. The quality depends on the stability of manufacturing process parameters and quality control system.

The results obtained using the presented methodology can be used for a detailed design of an improved manufacturing system and for further economic analysis regarding labour costs and costs associated with investments in automation and robotisation.

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