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Analysis of the Impact of Modernization of Machinery on the Quality of Castings Using Quality Management Tools

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Today's manufacturing industry, especially in the context of the metals industry, is constantly evolving towards ever more advanced technologies and efficient production practices. In this context, machinery modernization is becoming a key element in improving manufacturing processes. This article focuses on analysing the impact of machinery modernization on casting quality, using selected quality management tools. The article presents an analysis of the effects of the implementation of modern technology, automatic casting machines, on the quality of castings production. Using quality tools such as the Ishikawa diagram, Pareto-Lorenz and the FMEA method, the main causes of casting nonconformities, the frequency of occurrence of these nonconformities and the risks associated with them were identified for periods before and after the implementation of machine park modernization. The measurable benefits associated with the introduction of modern foundry technology in terms of improved casting quality were showed. Using quality tools, the quality improvement achieved was determined indirectly, while the level of improvement in casting quality after the modernization of the machine park was showed directly using the defect rate. It was also shown that, despite an increase in production efficiency and the level of quality of the manufactured products, the introduction of the new technology generated new quality challenges in the context of maintaining the stability of the casting process parameters as a result of a jump in productivity levels. The paper highlights the need to balance production efficiency with attention to casting quality, which was an important issue for the foundry studied.

Keywords: Casting, Modernization, Quality, Quality management, Quality tools, Quality analysis & evaluation

1 Introduction

In an era of dynamic technological progress, the industrial sector is constantly challenged to be efficient, innovate and remain competitive [1]. One of the key elements influencing product quality in the field of metallurgical production is the technical condition and modernity of the machinery park [2]. The modernization of the machinery park is becoming an integral part of the strategy of foundries seeking to improve their production processes and increase the quality of the casting products produced [3]. In the context of the foundry industry, where casting precision and durability are crucial, the analysis of the impact of machinery park modernization on the efficiency parameters of the production process, i.e. quality and efficiency paremeters, i.e. costs, among others [4], becomes a particularly important issue worth analysing. Indeed, increasing the effectiveness and efficiency of the production process is crucial to increasing the competitiveness of companies [5]. Modern casting machines provide greater efficiency in the casting production process, enabling shorter production cycle times, increased quality, productivity and reduced operating costs [6]. The analysis of the benefits resulting from an increase in casting quality levels due to the modernization of casting machinery is, in each case, an important justification for the costs incurred in their modernization.

The level of modernity of a machine in production closely correlates with the quality of the manufactured products [7, 8, 9]. Advanced technologies in machinery translate into precise and repeatable operations, automation of production processes and reduced production time [10]. Modern machines often have built-in quality control systems, enabling real-time monitoring of parameters, which results in the rapid detection of potential problems and supports the maintenance of a stable quality level. Flexibility and innovative technological solutions in machinery affect adaptability to changing production conditions [11]. The modernization of machinery involving the automation of production processes allows the elimination of routine and repetitive tasks, which not only reduces the time of the production cycles, but also eliminates human errors, which translates into an increase in the quality of processes and products [12]. Modern automated technical solutions are typically characterised by lower operating and maintenance costs, which translate into financial savings and increased operational efficiency [13]. Reduced maintenance costs, minimised failure rates, increased productivity and improved quality as a result of the introduction of modern production technologies translate into increased efficiency of production [14].

Quality tools are a set of tools used in the area of quality management, control and improvement [15, 16]. They can be divided into the old, classic, SPC tools and the new, management tools, of which there are seven each in both groups [17]. The significance of the seven traditional tools is evident, especially as customer demand rises while seeking improved product quality by lowering defective rate [18-21]. In addition to increasing the quality level, they can also be an important tool in reducing the organization's operating costs [22]. Substantial enhancements have been noted following the implementation of these traditional tools in both process potential capability and actual capability (Cp, Cpk), as well as in the reduction of defective parts per million (PPM) [23]. Quality tools provide significant support in the process of improving production and quality when implementing improvement concepts such as Lean or Six Sigma [24]. The implementation of quality tools in the company is supported by the functioning of a quality-oriented system, e.g. a quality management system according to the ISO 9001 standard and having a mature organizational culture oriented towards continuous improvement [25, 26, 27].

The main objective of the research carried out in this article was to analyse the impact of foundry machinery modernization on casting quality, using specific quality tools and quality indicators. The analysis was intended to provide practical guidance for companies to estimate and evaluate the benefits associated with changing technology in terms of improving the quality of manufactured products.

2 Methodolodgy

The research was conducted in a foundry located in Poland, in the Łódzkie Voivodeship. The main activity of the foundry is the production of pressure castings from Al-Si alloys. The foundry's annual production is approximately 2,400 tonnes of castings, covering a diverse range of up to 400 die castings. The foundry mainly supplies manufacturers in the automotive, household, electrotechnical, gas equipment, mechanical equipment, construction and control and measuring apparatus industries.

The product under examination is a so-called "cross-brace" - pressure casting in Al-Si alloys, characterised by three shoulder-shaped protuberances. It is used as a component of an automatic washing machine, playing a role in transferring the drive from the washing machine motor to its drum. Due to the importance of its function, there is a need to maintain a high level of workmanship, as the cross-brace is prone to breakage during washing machine operation.

The machinery stock of the foundry studied consists of vertical and horizontal high-pressure casting machines. The research covered the period before and after the introduction of the modernization of the machine park. The modernization programme included the replacement of old, worn-out pressure machines, so-called conventional machines, with new, modern machines operating unmanned in an automatic cycle, and the construction of production cells. The modernization of the machine park included the purchase and installation of 6 new machines - automatic and semi-automatic casting machines - and the modernization of one conventional machine to operate in a semi-automatic cycle. Working on the conventional and new machines differed in the degree of employee involvement in the process of operating these machines. On the conventional machines, all ancillary and preparatory and finishing operations, such as spraying the mould, pouring the mould, starting the piston, picking up the casting and depositing the castings, were performed manually by the worker. The new machines are automated machines, where the operator's role was limited to picking up the casting, depending on the type of machine, and visually inspecting whether the product was as required.

Using selected quality management tools and methods, as well as quality level indicators, an analysis of the impact of machine park modernization on the quality of manufactured castings was carried out. As indirect methods of assessing the quality level for the old and new casting technology, the results of the quantitative and qualitative analysis of casting nonconformities were taken into account, using the Ishikawa diagram, the Pareto-Lorenz diagram and the FMEA method. On the other hand, the result of the deficiency rate calculation before and after the introduction of the machine park modernization was used as a direct measure to assess the quality level.

An indirect assessment of the impact of modernization on the estimation of casting quality levels was carried out by identifying the causes of nonconformities arising after the die casting process on conventional machines (i.e. in the period before modernization) and on automatic and semi-automatic machines (i.e. in the period after modernization) using an Ishikawa diagram. The analysis of an Ishikawa diagram, also known as a cause-and-effect diagram or fish diagram, allows the identification of the various causal factors that can influence a given problem, in this case 'nonconforming products' in the problem categories analysed [28, 29, 30]. The number of causes of nonconformity in the Ishikawa diagram indicated the complexity of the problem of 'nonconforming products' before and after the introduction of the machine press upgrade. It was taken as a preliminary indicator of the complexity of quality problems for the periods before and after the introduction of the modernization. The main categories of causes of nonconforming products were identified based on the 5M principle (Man, Material, Machine, Method, Management) [31], with an indication of the critical problem categories. The analysis of the reduction in the number of instances of potential causes of nonconformity in all 5M problem categories for the period after the machinery upgrade provided an indirect snapshot of the impact of the machinery upgrade on casting quality.

The structure of the incidence of casting nonconformities was analysed for the periods before and after the introduction of modernization of the machinery. For this purpose, another quality tool was used, the Pareto-Lorenz diagram. A Pareto-Lorenz diagram is a tool used to analyse and present the percentage structure of nonconformities in a product or process. This diagram indicates the key types of nonconformities, identifying them according to their frequency of occurrence or the costs associated with them [32, 33, 34]. The structure of the incidence of casting nonconformities for the periods before and after the introduction of retrofitting using the Pareto-Lorenz diagram allowed a relative assessment of the magnitude of quality problems during these periods. Larger relative percentages of nonconformities in the compared periods suggested that a particular type of nonconformity had a more significant impact on the quality of the examined product. The use of the Pareto-Lorenz diagram made it possible to indicate the percentage structure of casting nonconformities and to note the difference between the incidence of nonconformities in the period before and after the introduction of automation. The analysis of the reduction in the number of casting nonconformities for the period after the machinery upgrade was a way to indirectly capture the impact of the upgrade on casting quality.

Using the FMEA method and its resulting indicator, the Risk Priority Number (RPN), an identification of the risks associated with the occurrence of casting nonconformities during the comparative periods studied was made. FMEA analysis focuses on identifying, assessing and managing potential risks and nonconformities in the process. By assessing the likelihood of a nonconformity occurring, the ease of its detection and its importance to the customer, FMEA helps prioritise risk areas in the production process steps and develop effective corrective and preventive actions [35, 36]. The objective of FMEA analysis is to minimise the risk of quality problems in the production process and improve the quality of manufactured products by eliminating potential errors, defects and nonconformities in the process [37,38]. The RPN is the number assigned to each potential risk in a process step, resulting from the multiplication of three components: the probability of nonconformity (P), the ease of detecting nonconformity (D) and the importance of nonconformity to the customer (S). The formula for RPN is $RPN = P * D * S$. The higher the RPN value, the more significant the risk associated with a given nonconformity is for the quality of the product [39]. In FMEA analysis, a critical value for the RPN indicator is set arbitrarily. One way to determine the critical value is to look at the resulting RPN indicator value. A level of 100 is often considered the critical value for the RPN indicator [39]. Once this level is exceeded for a given nonconformity, an effective plan to reduce its risk should be developed by identifying appropriate corrective and preventive actions. The analysis of the reduction of the RPN risk priority number for all casting nonconformities for the period after the machinery modernization, was another way to indirectly capture the impact of modernization on casting quality.

In the final stage of the analysis, the calculation of the defect rate, which is the ratio of the number of defective products to the total number of products produced, multiplied by 100, was carried out in order to express this rate as a percentage. The defect rate is a commonly used measure to monitor and evaluate the level of product quality [36]. The results of calculating this rate for the periods analysed are presented using a line graph. This allowed a direct assessment of the impact of machinery modernization on casting quality. The analysis of the reduction in the value of the defect rate, for the period after the modernization of the machinery park in relation to the period before the modernization, provided a measurable, direct snapshot of the impact of the modernization on casting quality.

3 Results

An Ishikawa cause-and-effect diagram was used to identify the causes of nonconformities in the production process of castings on a conventional machine. The main problem that was analysed concerned the formation of 'nonconforming products'. There were five main groups of causes that could influence the emergence of quality problems, and these were: man, method, machine, material and management (5M). The Ishikawa diagram in Fig. 1 shows the identification of potential causes of nonconforming castings resulting in a nonconforming product in terms of the 5Ms for the period before the machinery was upgraded.

The analysis of Fig. 1 shows that the main causes of nonconforming castings are mainly concentrated in the categories 'Human' and 'Machine'. The high number of operations performed by the casting machine, the monotony of the work, fatigue and extreme conditions, such as high temperature, favour human errors and mistakes and inaccuracies, which led to the frequent appearance of nonconformities in castings. In the case of a conventional machine, operating parameters that cannot be easily set, the lack of quick information about possible irregularities during operation and the inability to easily check the parameters of the machine at any given time were factors contributing to the occurrence of nonconformities. The 'Method' category, which includes the technology and the way the work is carried out, also influenced the occurrence of nonconformities. In contrast, causes related to 'Material' and 'Management' were assigned lower importance. A total of 28 causes were identified for the emergence of nonconforming products in the casting process carried out on conventional machines. The main factor determining the emergence of nonconformities was the large number of manual operations performed by the worker, which was an indicator of the 'old' production technology.

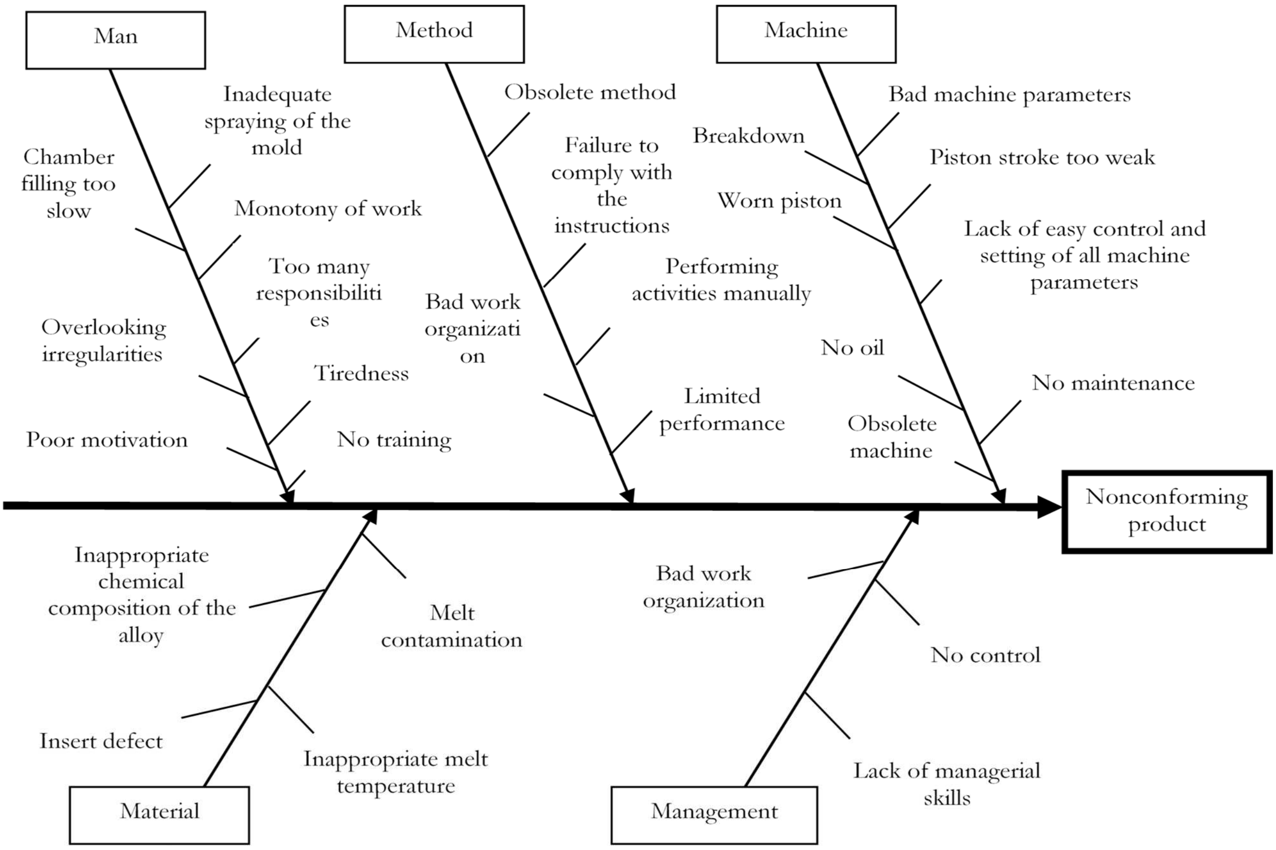

Fig. 1 *Ishikawa diagram for the period before the modernization of the machinery park*

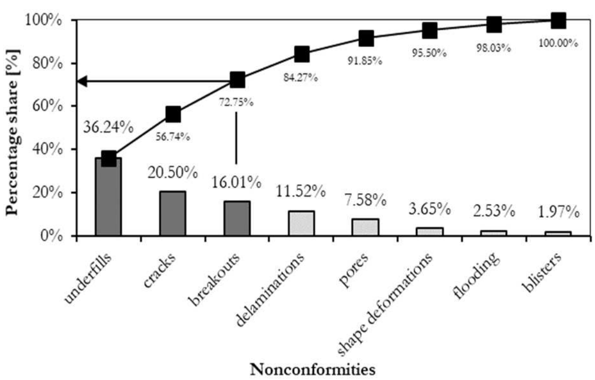

Fig. 2 *Pareto-Lorenz diagram of the product nonconformity structure for a selected period before the modernization of the machinery park*

An analysis of the types and percentage structure of nonconformities of the product under study for the selected period before the introduction of the modernization (selected month) showed the following proportion of each type of nonconformity as seen in the Pareto-Lorenz diagram (Fig. 2).

Analysis of the Pareto-Lorenz diagram shows that two nonconformities, underfilling and cracking, accounting for about 16% of all nonconformities, were responsible for almost 57% of the nonconforming products. A total of 356 nonconformities were recorded during the study period before the machine modernization. A total of 259 critical nonconformities (most common: underfills, cracks, breakouts) were found.

In order to analyse the risk of nonconformities in more detail, the FMEA method was applied. In the FMEA analysis carried out, nonconformities occurring throughout the casting production process were taken into account. The critical number for the value of the RPN index was arbitrarily set at 100 by the foundry's quality control department. Tab. 1 shows the results of the FMEA analysis for the period before the modernization of the machine park.

Tab. 1 *FMEA analysis for nonconformities of the analysed product for the period before modernization of the machinery park (mode value for: O = 4, S = 10, D =3, calculated RPN = 120)*

On.	Name of nonconformity	Effects	Causes	O	S	D	RPN	Corrective actions
N_1	Cracks	Product not compliant with the requirements	- sticking to the mold, - poor mold lubrication, - mold wear, - inappropriate solidification time (poor machine parameters).	5	10	3	150	- form review, - control of machine parameters.
N_2	Underfills	Product not consistent with the drawing	- inappropriate piston speed, -pressure too low, - low ironing, - metal temperature too low, - cold form, - machine failure.	6	10	3	180	- piston impact control, - checking the oil level in the machine, - melt temperature control, - proper heating of the mold.
N_3	Breakouts	Product not compliant with the requirements	- metal sticking to the mold (poorly sprayed mold), - core wear, - incorrect positioning of the casting on the trimmer by the employee.	4	10	3	120	- more precise spraying of the mold, - core replacement, - additional training for employees trimming castings.
N_4	Delaminations	Product not compliant with the requirements	- pouring the mold with melt "twice".	3	9	3	81	- additional employee training in casting, - replacing the pouring spoon with a suitable one.
N_5	Pores	Weakened product, non-compliant with requirements	- low ironing, - contaminated metal, - gassed metal, - inappropriate nitrogen level, - bad machine parameters (pressure).	4	9	4	144	- appropriate mold closure, - re-refining of the alloy, - checking machine parameters, - supplementing the nitrogen level.
N_6	Shape deformations	Product not consistent with the drawing, assembly problem	- uneven solidification of the alloy, - seizing ejector pins, - incorrect positioning of the casting on the trimming tool by the employee, - uncleaned trimmer.	3	10	4	120	- checking mold cooling, - checking the condition of ejectors, - additional employee training.
N_7	Flooding	Product not compliant with the requirements	- undersized insert, - inappropriate mold closure.	3	9	2	54	- checking the dimensions of the insert, - appropriate setting of the mold clamping.
N_8	Blisters	Weakened product, non-compliant with requirements	- low ironing, - contaminated metal, - gassed metal, - bad machine parameters (pressure), - inappropriate nitrogen level.	4	8	2	64	- appropriate mold closure, - re-refining of the alloy, - checking machine parameters, - supplementing the nitrogen level.

The most common (mode) values of the Occurrence (O), Severity (S), and Detection (D) indicators for the period before the modernization of the machinery are 4, 10, and 3, which gives the value of the RPN indicator = 140. The FMEA analysis shows also that in the production of a casting on a conventional machine, the highest risk of occurrence was for the following types of nonconformities: underfills (RPN=180), cracks (RPN=150), pores (RPN=144), breakouts (RPN=120), shape deformation (RPN=120). On the other hand, nonconformities such as delamination, blistering and flooding were the least likely to occur. Turning to the causes of nonconformities in the period before the introduction of the upgrade, human labour, the prepared alloy, the condition of the machine and its set parameters were quite important. Corrective actions to reduce the risk of nonconformities mainly concerned additional training of employees, the accuracy of the work performed and the control of all important process parameters. The risk of occurrence of individual nonconformities measured by the RPN index is presented in Fig. 3.

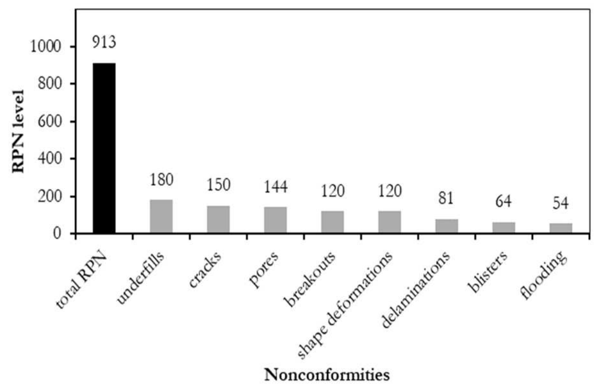

Fig. 3 *RPN level for nonconformities occurring in the casting production process on a conventional machine*

The total risk of all nonconformities measured by the RPN index for the period before modernization of the machine park was 913. 5 types of nonconformities out of 8 (62.5%) exceeded the critical value adopted for the RPN index equal to 100. These were such nonconformities as: underfills, cracks, pores, breakouts, shape deformations.

An Ishikawa diagram was also used to identify the causes of the nonconformities, casting this product on an automatic machine. The problem placed on the main axis remained 'nonconforming product' and the diagram was also drawn based on the 5M categories. Fig. 4 shows the Ishikawa diagram for the situation after the introduction of the machinery modernization.

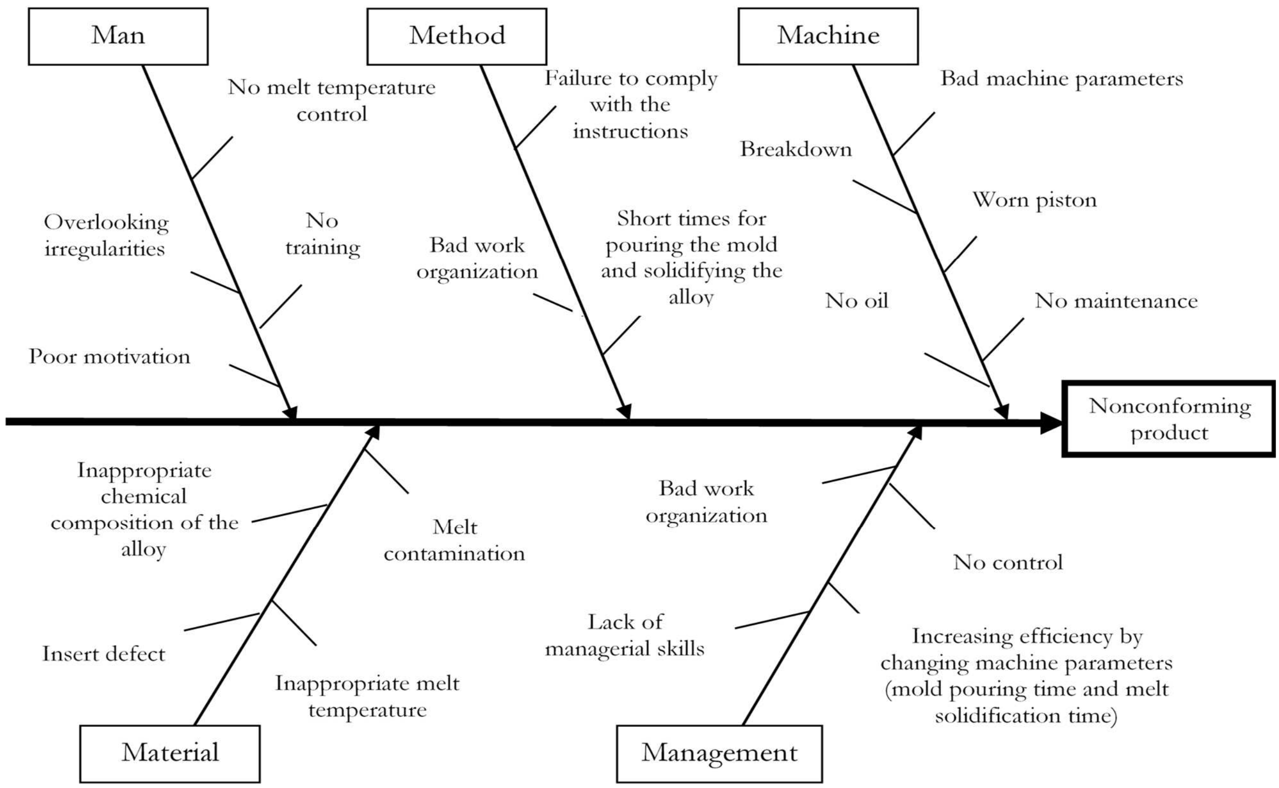

Fig. 4 *Ishikawa diagram for the period after the modernization of the machinery park*

A total of 20 potential causes of casting nonconformities were identified after the introduction of the upgrade. The introduction of automatic casting machines has minimised the contribution of the human factor to the causes of casting nonconformities to a very large extent. The role of the foundry worker on the new machines has been reduced to part acceptance, pattern inspection and checking melt temperature. The robot, working in place of humans, does not get tired and is much more efficient, while its proper programming eliminates the possibility of human error. On a modern machine, all parameters can be set and easily controlled on a single panel. It is also possible to check information about the operation of the machine at any given time and to view historical data of the machine's operation. The machine also provides a visual indication of any abnormalities, allowing the operator to react quickly. However, attention should be paid to the factor of the desire to increase productivity by changing the parameters of the machine, an important reason for the large number of nonconforming products produced on an automatic machine. The company, wanting to produce faster and more, also generates a larger number of nonconforming products. An Ishikawa diagram analysis of a foundry showed that the introduction of modernization reduced the potential causes of nonconformities from 28 for conventional technology to 20 for the new technology.

The production of castings on an automatic machine has not completely eliminated the problem of nonconforming products. They are also produced as in the case of casting on a conventional machine, but there are fewer of them in relation to the much higher production output. Seven nonconformities were observed, which caused the product to be classified as a defect: N1 - cracks, N2 - underfilling, N3 - breakouts, N4 - shape deformation, N5 - flooding, N6 - delamination, N7 - pores. The results of the analysis of the percentage structure of nonconformities for the period after the fleet upgrade are presented by means of a Pareto-Lorenz diagram in Fig. 5.

In the case of the new casting technology, nonconformities such as blisters, which occurred during casting production on the conventional machine, did not occur. Two nonconformities, i.e. underfills and breakouts, occurred most frequently and were also responsible for approx. 57% of defects. In both old and new technologies, underfills were the most common casting nonconformity. As a result of the introduction of the new casting technology, it was possible to reduce the number of casting nonconformities to 331, compared with 356 before modernization. A total of 243 critical nonconformities (underfills, cracks, breakouts) were found. The proportion of critical nonconformities therefore decreased from 256 to 243 (16 fewer cases).

The result of the FMEA analysis for the casting production period on the modern casting machine is shown in Tab. 2.

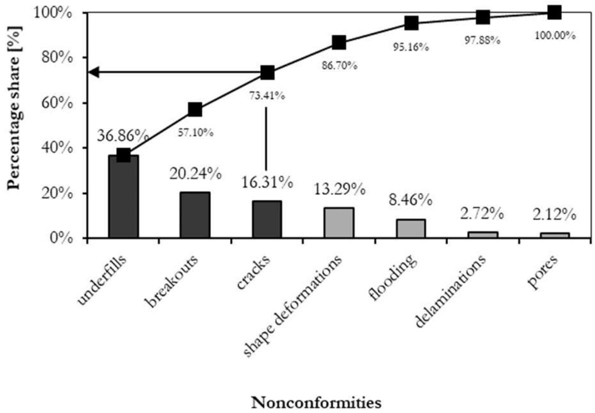

***Fig. 5** Pareto-Lorenz diagram of the product nonconformities structure for the period after the modernization of the machinery park*

***Tab. 2** FMEA analysis for nonconformities of the analysed product for the period after modernization of the machinery park (mode value for: O = 2, S = 10, D =3, calculated RPN = 60)*

On.	Name of nonconformity	Effects	Causes	O	S	D	RPN	Corrective actions
N_1	Cracks	Product not compliant with the requirements	- sticking to the mold, - poor mold lubrication, - mold wear, - inappropriate solidification time (poor machine parameters).	3	10	3	90	- form review, - control of machine parameters.
N_2	Underfills	Product not consistent with the drawing	- inappropriate machine parameters, - metal temperature too low, - cold form, - machine failure.	4	10	3	120	- control of machine parameters, - melt temperature control, - proper heating of the mold.
N_3	Breakouts	Product not compliant with the requirements	- metal sticking to the mold, - core wear, - incorrect positioning of the casting on the trimmer by the manipulator.	2	10	3	60	- control of the agent spraying the mold, - core replacement, - control of robot parameters.
N_4	Shape deformations	Product not consistent with the drawing, assembly problem	- uneven solidification of the alloy, - seizing ejector pins, - incorrect positioning of the casting on the trimmer by the manipulator, - uncleaned trimmer.	2	10	4	80	- checking mold cooling, - checking the condition of ejectors, - control of robot parameters.
N_5	Flooding	Product not compliant with the requirements	- undersized insert, - inappropriate mold closure.	2	9	2	36	- checking the dimensions of the insert, - appropriate setting of the mold clamping.
N_6	Delaminations	Product not compliant with the requirements	- uneven solidification of the alloy, - alloy contamination.	2	9	3	54	- additional employee training in melting, - re-refining of the alloy.
N_7	Pores	The product is weakened and does not meet the requirements	- bad machine parameters, - contaminated metal, - gassed metal.	3	9	4	108	- control of machine parameters, - re-refining of the alloy.

The most common (mode) values of the Occurrence (O), Severity (S), and Detection (D) indicators for the period after the modernization of the machinery are 2, 10, and 3, which gives the value of the RPN indicator = 120. It should be noted that as a result of modernization, the possibility of non-conformities (Occurrence - O) has decreased from the most common value of 4 (before modernization) to 2 (after modernization). Through the FMEA analysis, it became also apparent that the highest risk of nonconformities during the production process of the cross-brace in the new technology were nonconformities such as underfills (RPN=120) and pores (RPN=108). The lowest risk priority numbers were given to nonconformities such as breakouts, delamination and underfills. A summary of the RPN index for all nonconformities for the period after the machinery upgrade is shown in Fig. 6.

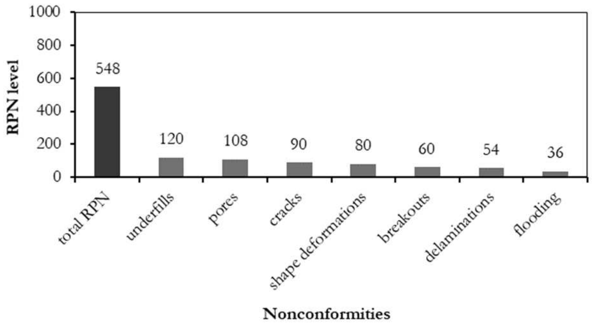

Fig. 6 *RPN level for nonconformities occurring in the production process of a casting on an automatic casting machine*

In the post-modrnisation implementation period, human-related causes were eliminated and the sources of nonconformities were mainly related to the prepared alloy and the relevant machine parameters. Corrective actions mainly concerned the control of machine parameters. After starting production on modern machines, the risk of nonconformities decreased by an average of one-third and, in the case of breakouts, by up to one-half. The risk hierarchy of some nonconformities also changed, e.g. pores received a higher RPN index value than cracks. The same was true for deformations of shape and breakages. The total risk of all the nonconformities measured by the RPN index for the period after machinery modernization was 548. After machinery modernization, only 2 nonconformities out of 7 (28.57%) exceeded the critical value (i.e. underfills, pores) assumed for the RPN index. The risk of each type of nonconformity for the comparative periods studied is shown in Fig. 7.

In order to determine the effects in terms of casting quality improvement after the introduction of the machine park modernization, the defect index was also calculated. The defect index was calculated as the ratio of the number of defective products to the total production volume of the casting in the successively examined months. The calculation of this ratio was carried out from October of year X to April of year X+1. The result of this calculation is presented in the line graph in Fig. 8.

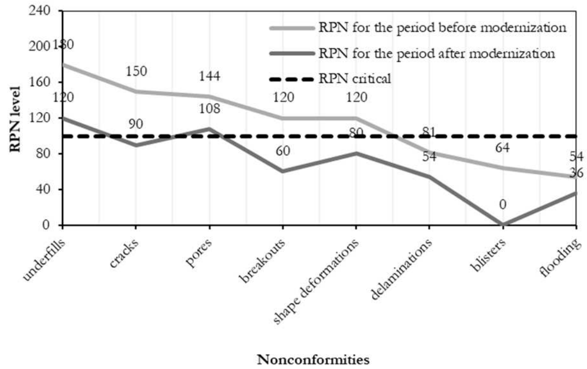

Fig. 7 *Comparison of the RPN index values for the period before and after the modernization of the machinery park*

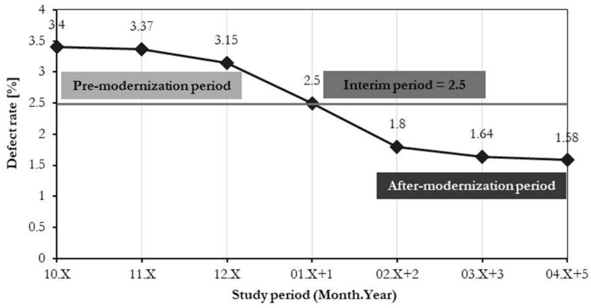

Fig. 8 *Comparison of the values of the defect rate of the analysed product in the entire period from October X year to October X+1 year*

During the period of time when the crossbows were produced on the conventional machine, the defect rate averaged between 3.00 and 3.50%. The month of January, the period of time when this casting was produced on both the conventional machine and the automatic machine, reached 2.50%. In the following months, the defect rate was between 1.50 and 1.80%. Relating the sum of the number of casting nonconformities to the total production volume for the periods before (3 months in year X) and after the machinery upgrade (3 months in year X+1), the defect rate for the period before the modernization was 3.4%, while after the upgrade it decreased to 1.67%. The modernization of the machinery park has therefore not only allowed the production volume to double, but also the level of defect occurrence to double.

A summary of the benefits resulting from the improvement in the quality of castings as a result of the transition from the "old" to the "new" casting technology is presented in Tab. 3.

***Tab. 3** A summary of the benefits resulting from the improvement of the quality of castings resulting from the transition from the "old" to the "new" casting technology*

	The number of potential causes of casting nonconformity read from the Ishikawa diagram	The number of casting nonconformities for the analyzed period read from the Pareto-Lorenz diagram	The total risk of nonconformity of castings read from the total value of the RPN index from the FMEA analysis	Defect rate [(number of nonconoforming products/number of all products)*100%]
Before modernization (A)	28	356	913	3.40%
After modernization (B)	20	331	548	1.67%
Reduction – value (A-B)/comparative approach [(A-B)/A]*100%	8/28.6%	25/7.02%	365/39.98%	1.73%/50.88%

As a result of the modernization of casting technology, specific qualitative benefits were achieved in terms of the number of potential causes of nonconformities, the number of nonconformities recorded in castings, the risk of nonconformities, and the defect rate. Thanks to the introduction of the new foundry technology, it was possible to reduce the number of potential causes of nonconformities by 8 cases (which was a decrease of 28.6% compared to the "old" technology), and the number of casting nonconformities was reduced by 25 cases (which was a decrease of 7.02%). The total risk of nonconformities decreased by 365 (a reduction of 39.98%). The defect rate decreased by 1.73%, which means that it decreased by 50.88% compared to the period before modernization. As a result, the benefits obtained in reducing the number of potential causes of nonconformities, identified nonconformities, the risk of nonconformities of castings, and the defect rate confirm that the modernization of casting technology contributed significantly to improving the quality and efficiency of the production process of castings in the tested foundry.

4 Conclusions

The aim of this article was to analyze the impact of machinery modernization on the quality of castings and to use quality management tools to assess this impact. The conducted research, in addition to demonstrating specific benefits resulting from the transition from the "old" foundry technology to the "new" one in the tested foundry, was also intended to provide practical tips for companies wishing to assess the qualitative benefits related to the change in production technology. The proposed approach for estimating the benefits resulting from improving product quality as a result of changing technology can be used by managers to justify the costs incurred as a result of modernizing the machinery.

The article presents the results of research conducted in a foundry located in Poland, specializing in the production of pressure castings from Al-Si alloys. The research concerned the modernization of the machinery, which involved replacing old conventional machines with modern automatic and semi-automatic machines. An analysis of the quality of castings before and after modernization was carried out using quality management tools such as the Ishikawa diagram, Pareto-Lorenz diagram and the FMEA method.

The analysis of the Ishikawa diagram for the period before modernization showed that the main causes of nonconformities concerned the "Man" and "Machine" categories. The large role of human work, monotony, fatigue, and the parameters of the conventional machine contributed to the frequent occurrence of nonconformities in castings. After modernization and the introduction of automation, the human factor was reduced, and the main reasons were focused on the prepared alloy and machine parameters. The Pareto-Lorenz diagram indicated that the two main nonconformities, i.e., underfills and cracks, were responsible for almost 57% of all nonconforming products before modernization. After modernization, a similar percentage of these two types of nonconformities was maintained, but the total number of nonconforming products decreased significantly. The FMEA analysis confirmed that before modernization, the greatest risk was associated with nonconformities such as underfills, cracks, pores, breaks, and shape deformation. After modernization, the risk of nononformities decreased, and the most prone to problems were gaps and pores. The defect rate improved significantly after the modernization of the machinery. It decreased by half on average, which confirms the effectiveness of the modernization carried out due to the level of quality of the manufactured products.

The research results confirmed that the modernization of the machinery had a significant impact on the quality of castings. Modern foundry machines operating in automatic or semi-automatic mode, equipped with advanced technologies and quality control systems, enable precise and repeatable operations, shorten the production cycle time, increase production efficiency, and reduce operational costs. Additionally, the automation of production processes reduced the number of cases of human errors, which also translated into improved product quality. The research results confirmed that the investment in the modernization of the machinery in the tested foundry based on the purchase of modern foundry machines was crucial for improving the quality of products and increasing production efficiency. At the same time, it was shown that increasing production efficiency as a result of switching to a new technology may also result in quality problems. Striving to significantly increase efficiency by changing machine parameters on modern automatic foundry equipment may generate a greater number of nonconforming products.

To sum up, the analysis of the impact of modernization of the machinery on the quality of castings using quality management tools confirmed the significant impact of the change in foundry technology on the quality of castings. The research conclusions indicate that modern technologies, properly implemented and used, can significantly improve the quality of manufactured products. The research conclusions also indicate that by using appropriate quality tools, companies are able to estimate the degree of improvement in production quality as a result of changing production technology. It has also been shown that increasing production efficiency through new technology may also result in quality problems, especially if appropriate parameters and procedures are not taken into account and adjusted. Therefore, it is important to balance production efficiency and quality, which requires careful analysis, monitoring, and adjustment of production processes.

Further research in this area will focus on assessing the effectiveness of the quality control methods used in detecting casting nonconformities. Moreover, it is worth continuing further research on new technologies and innovative solutions in foundry, which can further improve the quality of products and the efficiency of production processes.

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