PRODUCT DEFECTIVENESS ANALYSIS USING METHODS AND TOOLS OF QUALITY ENGINEERING

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Abstract: All production companies, regardless of the industry, face the problem of defective products. Removing the causes of the final product's defectiveness is connected with incurring additional costs, which reduces the efficiency of the production processes. That is why companies take measures to identify those causes which bear the most significance to ensuring the required product quality. The present article aims to indicate the tools of quality engineering that can be used to determine product defects and their impact on the quality of the final product. The article is based on a case study analysis of the example rock wool manufacturing company.

Keywords: defect, production, production process, FMEA, Ishikawa diagram, Pareto chart, quality costs

1 Introduction

Every manufacturing company encounters the problem of defective products. Unfortunately, even properly defined requirements, working production system and following procedures does not guarantee manufacturing a product compliant with the previously set requirements [1].

During the production process companies strive to fulfil all the necessary requirements, including quality requirements, while observing restrictions such as production costs. Practice demonstrates that fulfilling all requirements is not possible as no process takes place in ideal conditions. This is connected, among others, with the fact that machines (elements) wear and tear in the production process, unplanned breaks occur due to breakdowns, measurement devices wear out, materials with varying properties are used in the process, etc. All these factors translate into disturbing the work rhythm, unevenness of the production process, with human errors piling on top. That is why the problem of defective products exists in every company, which results in consequences such as increased production costs. In order to avoid this problem and fulfil the clients' expectations to the highest degree possible, measures should be taken that will allow for identifying the places in which defects arise as well as determine their causes.

2 The concept of defect

The concept of defect is defined in various ways. A defect is often identified with improper execution of the production process, which makes the product unusable for the end user. It can take many forms, although most commonly the term refers to the presence of errors or low quality. A defect is a non-compliance with the adopted requirements for the parameters that describe a given product. It is defined as a departure from the adopted requirements.

The concept of defect is connected with the concept of defectiveness, which is related to the technological defects or design flaws of a given product as well as other aspects connected with the necessity of making changes to the product. Defectiveness, therefore, can lead to client dissatisfaction and result in additional costs incurred by the manufacturer. Among the defects we can distinguish:

- important defects, i.e. one that makes it impossible to use the product or hinders its use,
- insignificant defects with relatively low impact on the functioning of the product and do not considerably decrease it usability.
- critical defects, which can lead to the development of conditions in which using the product would be dangerous or decreasing the capacity of certain functions of the product.

The occurrence of the aforementioned defects results in a non-compliant product. Non-compliance is understood as a state of a property that does not meet requirements, while a non-compliant unit is defined as a product with a number of non-compliances exceeding the permissible limit or one which contains a defect that causes its complete unusability [2]. According to the ISO 9000:2005 standard, a non-compliance (3.6.2) – failure to meet a requirement 3.1.2) [3].

Occurrence of a non-compliance does not facilitate quality, can be connected with a failure to meet the requirements related to the standards, quality documentation, legal regulations, requirements of the parties to the contract, client requirements or other parties concerned. Only defects that have been confirmed, that is supported with evidence, can be treated as non-compliances. The following categories of non-compliances are distinguished:

- systemic – defects detected in the quality management system,
- accidental – a requirement is not met, but without any major consequences.

Non-compliances are also divided into:

- small non-compliances – isolated, proven case of a requirement not being met,

- big (critical) non-compliances – defects of the entire system, a systemic non-compliance or alternatively a large number of non-compliances with the quality management system.

Moreover, documenting a non-compliance requires:

- indicating the requirement that has not been met,
- describing the nature of the non-compliance,
- demonstrating proof.

The reference to the requirement should be precise. Formulating the non-compliance should be clear, unambiguous, concise, while the proof needs to be documented and sufficiently detailed. Upon discovering a non-compliance, corrective measures (removing the cause of the non-compliance) are taken.

3 Defect detection

At present, any production defects are detected outside the production line at the last stage of production, which is linked to a great loss of time and additional financial expenses as well as generates undesirable wastes.

Every manufacturer strives to ensure fault-free production and minimise the losses on production lines, which translates into ensuring the economic efficiency of manufacturing activities. Fault-free production at a minimal level of waste generation results in a more balanced and competitive manufacturing industry, which is becoming the standard in modern manufacturing. The primary goal of every company is reliable and environment-friendly production without any defects and wastes. That is why new equipment and program solutions are being developed that bring innovation in terms of technology, modelling and methodology to integrated production quality control systems. At the same time, companies are introducing quality cost controlling for planning and monitoring the cost of measures aimed at ensuring the proper quality of products. These measures aim to reduce production costs, shorten stoppage time and minimise losses while simultaneously making it possible to manufacture safer products of desired quality.

Regardless of the place in which the defect was detected (at the input, in the middle or at the end of the production process) the process needs to be analysed in order to take such measures that will minimise the possibility of the problem occurring in the future. Early detection of a defect leads to streamlining of the production process, higher quality, product durability and has significant impact on production and quality costs.

Detection of defects is possible only through quality checks, which are responsible for assuring the quality of the product in the course of production, after the production process and in the trade [4].

The identified defective (non-compliant) product should be marked in such a way as to prevent accidental use. Dealing with such a product consists in [5]:

- taking measures aimed at removing the non-compliance (correction, corrective measure),
- permitting the use of or repurposing the product for other uses (re-qualification of the product),
- action aimed at preventing the product from being used for its original purpose,
- in the case of correction, the defective product must be verified again.

4 Production process of rock wool

Mineral wool is a commonly used insulating material (Fig. 1). Production of mineral wool is a complex process whose course depends on the type of product produced. The technology of rock wool production uses basalt, gabbro, dolomite, limestone as well as slag and coke (lowers the melting point). The wool production process starts with measuring the correct proportions of raw materials and placing them in a special cast iron oven where the coke (used as fuel) produces a high temperature of about 1400-1500°C during combustion. As a result of the melting, liquid rock mass flows out of the furnace, dropping onto discs that spin at a speed of several thousand revolutions per minute. These discs break up the pig iron, converting it into fibres, which are then cooled with air and collected in a settling chamber in the form of a carpet of wool. During the formation of fibres, binder and hydrophobic agents are added. From the settling chamber, the wool rug is directed onto the technological line, where it is formed by compression and distortion of the fibres in many directions.

Fig. 1. Rock wool

The next step is a polymerization chamber where the wool is heated to a temperature of about 200°C to fully polymerize the added resins and stabilise the material before its final treatment. After cooling the carpet, at the end of the line the rock wool is cut to the specified dimensions and then packed in foil.

Mineral wool is characterised by the following properties:

- thermal isolation (low heat conductivity coefficient),
- incombustibility and fire resistance,
- sound absorption capacity,
- size and shape stability,
- mechanical strength, elasticity,
- biological and chemical resistance,
- waterproofness and vapour permeability.

5 Analysis of product defect formation [6]

The case presented concerns a company in which studies were conducted to identify defects in the product, determine the causes, and implement preventive measures that reduce the number of defective products. To achieve the goal, we used quality engineering tools in the form of the Pareto chart, the Ishikawa diagram and FMEA.

In the first stage, the most common defects that arise in the production process of rock wool were analysed. Four main groups of defects were identified, outlying eight main causes, namely:

- improper wool colour,
- lack of declared product properties (i.e. the compressive strength and tensile strength),
- slab dimension non-compliance,
- improper softness of the slab (locally).

Table 1 presents the causes, frequency of their occurrence per year as well as their percentage share.

Table 1. List of causes of defects and their number per year

Cause No.	Type of defect	Cause of the defect	No. of defects	Share %
1	Improper wool colour	Too high shaft furnace temperature	30	9.7
2		Clogged defibrator	60	19.4
3	Lack of declared product properties	Too high resin temperature	15	4.8
4		Uneven spraying on the fibre	80	25.9
5		Wrong fibre misaligning machine settings	28	9.1
6	Dimensional non-compliance	Wrong saw blade dimension settings	50	16.2
7		Blunt saw blade	14	4.5
8	Slab locally soft	Improper functioning of the fibre misaligning machine	32	10.4

Next, the causes presented in Table 1 were sorted in decreasing order and the cumulative value was calculated (Table 2).

Table 2. Causes of rock wool defects

Cause No.	Cause of the defect	No. of defects	Share %	Cumulative value %
4	Uneven spraying on the fibre	80	26	26
2	Clogged defibrator	60	19	45
6	Wrong saw blade dimension settings	50	17	62
8	Improper functioning of the fibre misaligning machine	32	10	72
1	Too high shaft furnace temperature	30	10	82
5	Wrong fibre misaligning machine settings	28	9	91
3	Too high resin temperature	15	5	96
7	Blunt saw blade	14	4	100

The above juxtaposition shows that the main causes that generate more than 80% of all defects are:

- uneven spraying on the fibre,
- clogged defibrator,
- wrong saw blade dimension settings,
- improper functioning of the fibre misaligning machine,
- too high shaft furnace temperature.

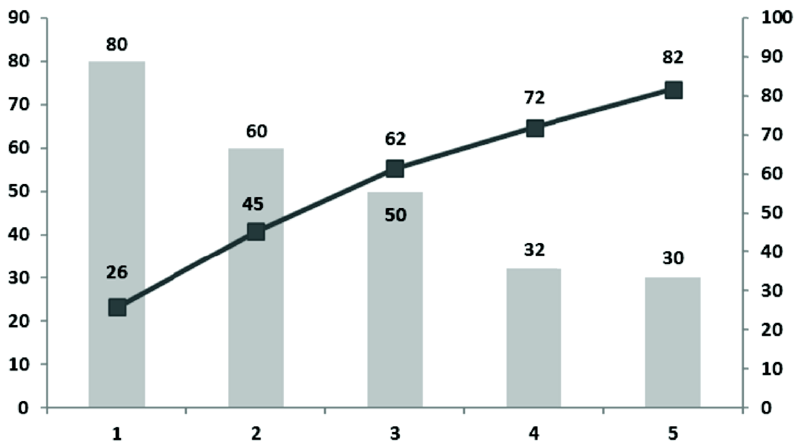

Fig. 2. Pareto-Lorenz diagram for the causes of defects in rock wool

The Pareto-Lorenz diagram (Figure 2) was narrowed for five main causes, which represent more than 80% of all defects (in accordance with the ABC principle).

The use of Pareto analysis allows us to consider the causes of the four major defects in the mineral wool production process. On the other hand, using the Ishikawa Diagram (Figure 3), we can show the reasons for potential defects of the manufactured product in the following areas:

- machine,
- material,
- people,
- method,
- management.

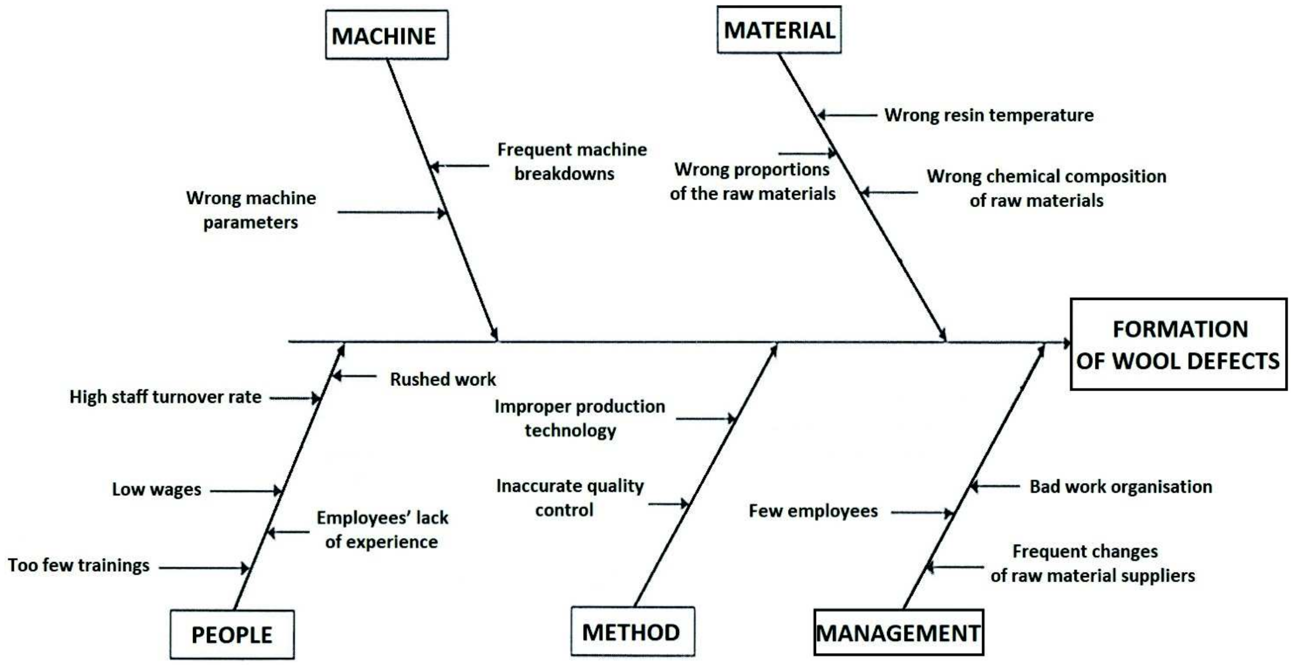

Fig. 3. Ishikawa diagram of the rock wool defect formation causes
Source: graph based on [6]

In this case, the Ishikawa diagram allowed us to clearly classify the causes of mineral wool defects. When analysing the diagram, it can be seen that the formation of defects in the production process of rock wool depends mainly on human factors such as:

- employees' lack of experience,
- small number of trainings,
- rushed work,
- high employee turnover, mainly due to low wages.

Further analysis of the diagram allows us to formulate conclusions about the desired improvement measures. The company should pay more attention to:

- more detailed quality control conducted at the earlier stages,
- motivating employees by directing their actions at ensuring product quality,
- raising the qualifications of production employees,
- increasing the number of production employees along with reducing the turnover rate.

The above list clearly indicates the important role of human resources in the production process. The success of the production process, resulting in fewer defective products, is largely dependent on skilled and experienced workers, which may translate into the financial sphere of production management [7].

For a more in-depth analysis of causes and effects of defects, another quality engineering tool was used: the FMEA (Failure Mode and Effects Analysis), i.e. an analysis of types and effects of possible failures [8, 9]. FMEA for defects in the rock wool mineral production process is presented in Table 3.

Table 3. Analysis of causes and effects of rock wool defects

Defect No.	Potential defect	Potential effects of the defect	Potential causes of the defect	Preventive measures	Zn	Cz	Wy	WPR	Results of action				
									Improvement measures	Zn	Cz	Wy	WPR
1	Improper wool colour	Customer complaints	Too high shaft furnace temperature	Constant monitoring of the lava-smelting furnace	8	3	1	24	Automatic control of the furnace temperature	8	2	1	16
			Clogged defibrator	More frequent cleaning of the machine	8	5	1	40	Checking the condition of the machine before starting a new batch	8	2	1	16
2	Lack of adequate strength properties	- Customer complaints - Product not maintaining stable dimensions and shape during use	Too high resin temperature	Stricter control of the raw material supplier	9	2	1	18	Analysis of the raw material	9	1	1	9
			Uneven spraying on the fibre	Monitoring the technological installation	9	4	2	72	Increasing the number of quality inspections	9	2	1	18
			Wrong fibre misaligning machine settings	Setting the machine correctly	9	5	1	45	|Increasing the monitoring of the machine's parameters	9	3	1	27
3	Dimension and shape non-compliance	- Making adjustments - Customer dissatisfaction - Remanufacturing the product - Increase in production costs	Wrong dimension settings on the saw	Correcting the saw settings	5	7	2	70	Purchase of more precise measurement tools	5	3	1	15
			Defects of the cutting tools	Replacement of the cutting knives	5	4	2	40	More frequent maintenance of the cutting tools	5	3	2	30
4	Slab locally soft	- Improper functioning of the fibre misaligning machine - Manufacturing of a new product -Increase in costs - Delays in product shipments	Wrong settings of the fibre misaligning programme	- More precise instructions - Employee training	9	4	6	216	Creating a more intuitive programme, training employees in this regard	9	3	6	162
5	Damaged collective pallet	- Increase in the amount of waste - Increased order completion time - Additional costs	Improper transport, lading and storage of the pallets	Packing the product more thoroughly, proper storage, more careful lading	9	4	2	72	Monitoring the safe packaging of the product and supervision of the warehouse hall	9	2	2	36
6	Lack of moisture resistance	- Increased wetness - Failure to meet requirements - Product cannot be used	Inadequate proportions of added binders and hydrophobic agents	Improving the process of adding binders and hydrophobic agents	10	2	6	120	Increased control of added components and samples for analysis	10	1	6	60

Use of the FMEA can help prevent the effects of defects that may occur during the design and manufacturing stages and indicates potential defects that may occur and result in the production of a defective product. In the case described, the assessment was made on a ten-point scale and included three criteria:

1. defect occurrence risk – Z_n,
2. potential for detecting the cause of the defect – C_z,
3. importance of the defect to the user – W_y.

For these three criteria, the WPR number is calculated, which indicates which defect may occur at the earliest and which should be paid the highest attention.

$$WPR = Z_n \cdot C_z \cdot W_y$$

Table 3 summarizes the WPR values obtained before and after the FMEA. The corrective measures introduced have resulted in a reduction in the WPR values by half or more for each type of defect.

Table 4. WPR values before and after the FMEA

Defect No.	Sum WPR		Valume in %	
	before	after	before	after
1	64	32	9	5
2	135	54	19	8
3	110	45	15	6
4	216	162	30	23
5	72	36	10	5
6	120	60	17	9

Table 4 shows the effects of corrective measures. The data contained in Table 4 are shown graphically in Figure 4.

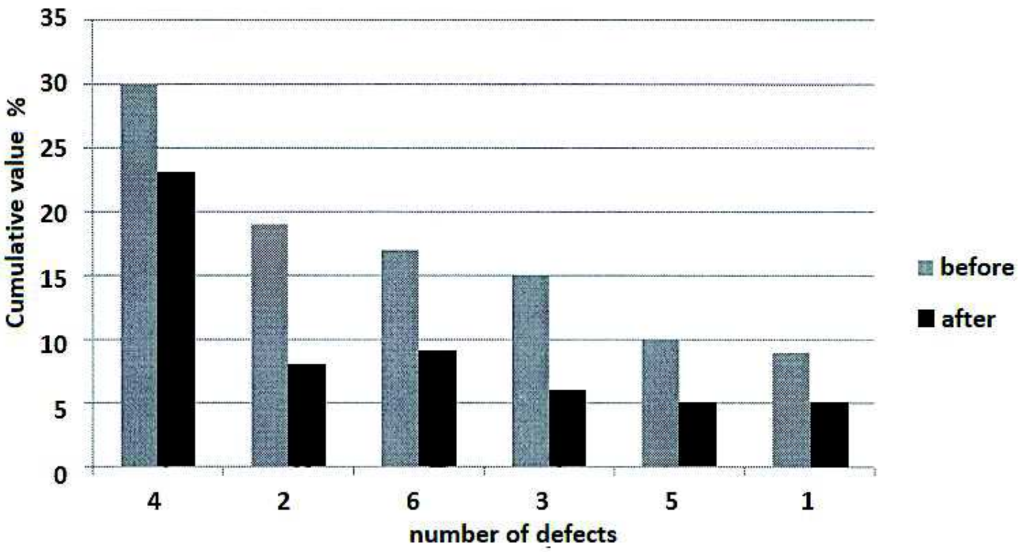

Fig. 4. Ordered diagram of defects "before" and "after" the FMEA
Source: figure based on [6]

The defects have been sorted in descending order, giving a clear picture of their significance. At the same time, it indicates the recommended order in which the defects in the production process should be removed.

Conclusion

The production process of the rock wool is a multistep process and the finished product is affected by many factors from the human factor, the raw materials through the manufacturing process to the storage. This article recommends a method for analysing a manufacturing process aimed at detecting defects and identifying areas for corrective actio. To this end, the following quality engineering tools were proposed: the Pareto-Lorenz diagram, the Ishikawa diagram and the FMEA method. In-depth analysis using these tools identified the most common defects that result in failure to meet specific quality requirements and thus customer expectations. The tools selected also made it possible to identify the causes of defects and their effects on the quality of the final product. Defects discovered after the production process can rarely be corrected, which translates into an increase in the costs of the production process and reduced economic efficiency of the company. For this reason, it is important to make a financial commitment to eliminate the identified non-compliances in order to reduce defect rates and thereby maintain the desired level of production costs. The quality engineering tools proposed can be extended to include quality cost control, which would allow for greater consideration of the issues of product defects and improvement of production processes. In the authors' opinion that the methods indicated can also be used in the area of analyses aimed not only at the technical but also the economic consequences of product defects.

CZ PL
PŘEKRAČUJEME HRANICE
PRZEKRACZAMY GRANICE
2014—2020

EVROPSKÁ UNIE / UNIA EUROPEJSKA
EVROPSKÝ FOND PRO REGIONÁLNÍ ROZVOJ
EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

Projekt jest współfinansowany ze środków Europejskiego Funduszu Rozwoju Regionalnego oraz z budżetu państwa RP „Przekraczamy Granice"

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ANALIZA WADLIWOŚCI PRODUKTU Z WYKORZYSTANIEM METOD I NARZĘDZI INŻYNIERII JAKOŚCI

Streszczenie: We wszystkich przedsiębiorstwa produkcyjnych niezależnie od branży, występuje problemem wyrobów wadliwych. Usunięcie przyczyn powodujących wadliwość produktu końcowego, wiąże się z poniesieniem dodatkowych kosztów, co obniża efektywność procesów produkcyjnych. Dlatego też, przedsiębiorstwa podejmują działania aby rozpoznać przyczyny, które mają najistotniejsze znaczenie dla zapewnienia wymaganej jakości. Celem artykułu jest wskazanie możliwych do wykorzystania narzędzi inżynierii jakości dla określenia wad produktu i ich wpływu na jakość produktu gotowego. Artykuł opiera się na analizie case study w oparciu o przykład producenta wełny mineralnej skalnej.

Słowa kluczowe: wada, produkcja, proces produkcyjny, FMEA, diagram Ishikawy, diagram Pareto, koszty jakości