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THE APPLICATION OF SELECTED QUALITY TOOLS IN ANALYSING THE REASONS FOR DISCREPANCIES IN WET REFRACTORY MORTAR MANUFACTURE

Monika KIEĆ[1*], Marek BUGDOL[2]

[1] Jagiellonian University, seminar student at the Department of Quality Management. Quality Manager at Vesuvius; monika.kiec@op.pl, ORCID: 0000-0002-9888-1170
[2] Jagiellonian University, Department of Quality Management; marek.bugdol@uj.edu.pl, ORCID: 0000-0001-9993-7765
* Correspondence author

Abstract: The basic objective of this paper is to present the possibilities of applying selected quality tools in analysing the reasons for discrepancies as exemplified by the process of manufacturing wet refractory mortars. Using various methods and tools, the authors looked for the root causes of a quality rejects occurrence. The following selected methods and tools were used: analysis of variance – ANOVA, the individual moving range (I-MR) chart, SIPOC process mapping, analysis of regression, identification of potential root causes of a problem – 7M, Gauge Repeatability and Reproducibility (GRR). The paper shows how it is possible to search for the causes of quality rejects by means of deliberately selected tools and methods and to successfully decrease the number of discrepancies after introduction of the appropriate corrective actions. The authors indicate how it is possible to analyse the processes of manufacturing wet refractory mortars and what can be done in the situation when a faulty measuring system (returning seriously erroneous results) is the reason for a lack of or lower detectability of wet mortar flaws as it has affected the accuracy of feeding of all components of the recipe, as well as the consistency, moisture content, and hardness/softness of mortar. The collected analysis results allowed the authors to conclude that there were seven probable root causes influencing the hardening of mortar and the loss of its primary functions. This paper could be useful for those wet refractory mortars manufacturers who find it difficult to build their knowledge about product properties based on available publications sources.

Keywords: quality tools, root cause analysis, wet refractory mortars, ANOVA, Gauge Repeatability and Reproducibility GRR.

Introduction

In the case study described below, the authors' primary objective was to present the possibilities of applying selected quality tools in identifying the root cause of wet mortar hardening, by analysing the reasons for discrepancies as exemplified by the process of manufacturing wet refractory mortars. The secondary objective of this paper is to inform the reader of the technological process and the basic product quality properties controlled during the process of manufacturing, as well as the major quality issues leading to loss of product primary and secondary function.

Wet mortars are refractory products used as a binder for high alumina bricks or concrete masonry units employed commonly as thermo-mechanical elements of fireproof structures of furnaces used in the manufacture of steel, iron, glass or aluminium (Andreev et al., 2014). Mortars fulfil an important function in the integrity of the entire structure, therefore, they consist of very fine fractions of a material in order to resist corrosion when in contact with a liquid metal (Routschka, 2004, pp. 269-271). Wet mortars are not a particularly complex product in terms of the complexity of a raw material recipe, but they constitute a challenge in the technological sense, where the quality of raw materials, the stability of a technological process or chemical processes taking place inside mortar, create a complex network of relationships.

Wet mortars are made of formulation liquid and powder elements. The process equipment used for manufacturing of wet mortars consists of a dry powders dosing station placed over a 2,5T charge mixer, with discharge system located underneath this. Powders are delivered in 25kg paper bags. The number of bags required per total mix charge is calculated as actual mixer charge multiplied by ratio [%] of material content required by formulation, and divided by size of the bag – 25kg. As result of this approach, the content of each ingredient is rounded to the full 25kg bag, except for small content ingredients (below <1% in recipe), where 0,01kg weighing accuracy is applied. In addition to powder elements, there are two different liquid components added by means of separate pumping systems, enabling weighing accuracy of +/- 1kg. Both powder and liquid ingredients are mixed together in the paddle type mixer for a specified time length. Underneath the paddle mixer there is a valve used for material controlled evacuation and packing at the packing station. Operators discharge the mortar from the mixer to the plastic buckets and then weigh the content on the scale. Each bucket is sealed with a plastic lid. Individual bucket are identified with a label and packed into cardboard or wooden crates. The packed product is distributed worldwide and used within product's lifetime, counted for 12 months from the manufacturing date. The quality of the finished product is verified after the mixing process, according to the guidelines listed below.

The product requirements that must be met within the process, are described in technological instructions constituting process input. In order to achieve output product parameters, particular input requirements have to be met for raw materials, a mixer, a recipe, packaging, metrology and production volume. The process suppliers are manufacturers of natural and synthetic raw materials that monitor their own respective manufacturing processes and are obliged to carry out raw materials acceptance inspections and to submit inspection certificates specifying inspection results with respect to established limits. The supplier is obliged to notify the manufacturer of wet mortars in advance of any changes in the process that could have a material impact on the quality or availability of a particular raw material. A recipe or a composition of raw materials and the percentage shares of raw materials is prepared by the research and development department (R&D) in a manner ensuring the fulfilment of the customer's requirements. The R&D department provides a recommendation for conducting the technological process. This is used subsequently by the quality control team to prepare technological instructions for the process. Another team is responsible for metrological supervision over all pieces of equipment included in a control plan document – those used both in the course of production operations and in the quality control laboratory. A typical quality parameter assessed during the final inspection of a product is mortar consistency, moisture content, and particle size distribution. An additional parameter defined at the stage of product development and checked periodically is the percentage shares of chemical groups such as aluminium oxides Al2O3, silicon oxides SiO2, alkalis K2O and Na2O, the metal content in Fe2O3, TiO2, MgO, CaO, as well as strength and resistance parameters tested after the mortars have dried (Guler, and Artir, 2007). The aforementioned qualities of mortars have a secondary function; if the requirements set forth in a specification are not met, this may shorten the product's shelf life period or result in dissatisfaction of the customer. The primary function of mortars is their readiness for use immediately after the end user opens the packaging. A loss of the primary functions may result in the customer's extreme dissatisfaction, delays in shipment, or additional costs for both the customer and the supplier. That is why, in addition to above tests, a visual/manual assessment of the mortar softness is conducted within 24h and 7 days from manufacturing, to confirm its usability. This is a kind of “go/no-go” test, where the operator compares 2 extreme states of the mortar: usable (soft) and not usable (rock hard mortar).

Mortar hardening is a condition of irreversible setting that makes it impossible to use, which constitutes a loss of a primary function. Mortar hardening is the main reason of product discrepancies. The manufacturer of wet mortars had been trying to cope with the problem for over a year. In 2017, the percentage of manufacturing rejects calculated as the ratio of the tonnage of the non-compliant/hardened mortar to the tonnage of the total mortar output was as high as 20.7%. As the target ratio was not more than 1%, it was no surprise that the factual ratio, which was twenty times higher, resulted in thirteen complaints received from customers. Problems cropped up with the timeliness of product shipments and the production volume had to be increased to 152.5% (higher volumes and costs of orders for raw materials, higher demand for workforce, more frequent repairs, expensive air freight shipments).

Literature review

The previous publications analysed the influence of various physical and chemical factors on the utility of refractory mortars. For example, tests focused on the influence of the setting system on the compressive behaviour of refractory mortars. It was concluded that in the case of refractory linings for industrial furnaces, the compressibility of mortars was of primary importance for the thermo-mechanical integrity of the structure (Andreev et al., 2014). The scope of the tests included the compaction and shearing of refractory mortars (Andreev et al., 2017), as well as the influence of waste refractory brick on the thermal and mechanical behaviour of mortars (Saidi, and Safi, 2014). At present, there are no publications that would indicate ready-made solutions concerning the improvement of particular wet refractory mortar manufacturing processes by means of various quality methods or tools. Thus, downstream customers had to face different quality problems caused by the changeability, interdependence, and causality of processes, as well as the organization's social and technical systems.

In contrast to the situation of remedial action for product variability, there is extensive literature on the possibilities of applying selected quality methods or tools. Analysis of variance "is a statistical method of establishing the existence of differences among means in a few populations" (Hamrol, 2007, p. 347). Analysis of Variance (ANOVA) techniques are applied to quality engineering. ANOVA is also the cornerstone for uncovering the effects of design factors on performance (Giloni et al., 2005). Moreover, it can be used in searching for solutions to various problems with quality. For example, in the processes of binding different materials (Harizam et al., 2018), reusing the same materials (Harizam et al., 2018)[1], improving product quality during the processing of thin-walled elements (Bolar et al., 2018), cutting various materials (Mullick et al., 2017). This method is applied where it is important to select carefully process parameters in order to achieve required efficiency or to look for variability in order to identify the root causes of a problems.

The I-MR chart is a type of a control graph used commonly in the case of continuous data. It was developed by Walter Shewart. I-MR is used to monitor process stability, to determine whether a process is stable or not and ready for improvement. Of note: control charts are very effective tools that are used for detecting the assignable cause of variation (Moraditadi and Avakhdarestani, 2016).

As proposed by Deming, SIPOC is an organization system model used in process management and improvement (Cao et al., 2015). Such a model constitutes a basis for developing a process map. The acronym SIPOC consists of the first letters of the following English words: Supplier, Input, Process, Output, Customer. The main task of this model is to join the customer with the process and the supplier, as well as to identify the key "inputs" and requirements. Requirements flow in the opposite direction, i.e. from the customer to "outputs"

[1] A statistical approach for assessing the effect of powder reuse on the final quality of AlSi10Mg parts produced by laser powder bed fusion additive manufacturing (Del Re et al., 2018).

and from the process to “inputs”. “SIPOC is also used in marketing management to fulfil customer need, customer satisfaction, concerns of stakeholders and the community” (Yeung, 2009, p. 312).

Analysis of regression is used “to determine relationships among the input quantities of a process and the characterizations referred to as results” (Hamrol, 2007, p. 350). “7M” or the identification of potential root causes of a problem comprises the following seven categories: material, man, machine, method, measurement, management, Mother Nature. It was developed on the basis of the commonly used Ishikawa diagram (Ćwiklicki and Obora, 2009, p. 61). The GRR (Gauge Repeatability and Reproducibility, % GRR) method is used to examine continuous data (e.g. height, length, width, diameter, weight, viscosity, etc.), as well as attributive data (e.g. the presence or absence of a defect). It is used to assess the reliability of measurement results. When measurements are taken, the following types of variability are taken into consideration: variability of parts (differences among manufactured parts), variability of assessors (reproducibility of measurement results and differences among people assessing a particular process or product feature) or variability of equipment (variability of instruments used to measure a given feature) (Jay, 2017). Reliable measurement systems are essential for the success of an organisation. Gage repeatability and reproducibility (GRR) studies assess this measurement system's capability (Waseem et al., 2015). Root cause analysis (RCA) is a method of problem solving used for identifying the root causes of faults or problems (Wilson, 1993). It finds practical applications in many spheres of life. Root cause analysis (RCA) could help understand better problems in maintenance with system viewpoint, discover the true root cause of failures, and other appropriate solutions to discard maintenance rework (Lee, and Chang, 2012).

Research methodology

The following research methodology was used to address the said objective.

- literature review (using the Academic Search Complete data base),
- process analysis and observations, process and quality data analysis with application of following tools:
  - analysis of variance (ANOVA),
  - Individual Moving Range (“IM-R chart”),
  - technological process mapping by means of SIPOC,
  - analysis of regression (Fitted Line Plot),
  - identification of potential root causes of a problem – 7M,
  - Gauge Repeatability and Reproducibility (GRR).
  - Root Cause Analysis (RCA).

Analysis of the reasons of discrepancies occurring in the process of manufacturing wet mortars

The first stage of the process diagnosis was preparation of a high level process map. For this purpose, the SIPOC model was used (Figure 1).

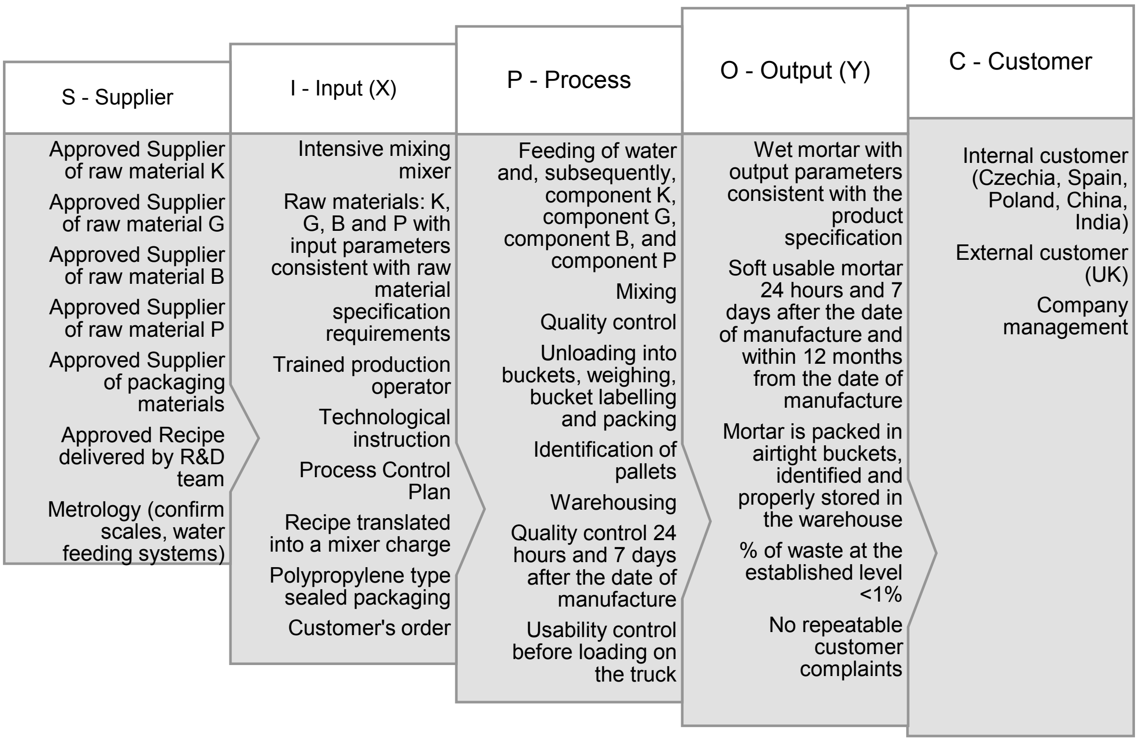


Figure 1. SIPOC process map. Source: The authors' work based on their own sources.

The customers of the process are both internal and external users of the mortar. The company management looks forward to a foreseeable profit generated from the stable sales of the product.

The customer requirements are specified in the input data for the process. A product specification sets forth allowable limits for the particular parameters of the finished product.

The organization's own requirements are set forth in terms of the allowable quantity of waste, i.e. not more than 1% and no repeatable customer complaints.

The process map allows the user to move from the general level to the more detailed level and identify process parameters that are critical to quality and have to be met if the customer is to receive a product meeting their established expectations.

Subsequently, an attempt was made to arrange the potential causes of the problem by grouping them according to the following "7M" categories: material, man, machine, method, measurement, management, Mother Nature, as per Table 1 below.

Table 1.
The identification of the potential root causes according to the 7M categories

PROBLEM: HARDENING OF WET MORTARS						
Category 7M /RCA Subgroup (A÷L)	**A**	**B**	**C**	**D**	**E**	**F**
1. Material	Material G: too fine, its quantities added to the mixer are too large/small	Material K: the specific surface area of grains is too small; porosity is too high; density is too low; quantity too large/small	Material B: ratio of Na to Si <2.05; It will not dissolve in cold water	Material P: its addition is too large, it does not dissolve in water	Water in the mixer: its temperature is too low <10°C for the components to dissolve in water	Non-airtight plastic buckets /exposure to air/ or buckets with low resistance to pressure
	G	**H**	**I**	**J**	**K**	**L**
	Finished product: the fine fraction (<63um) content is too high	Finished product: it is too hot during unloading operations (>30°C)	The raw material is moist and lumped (it will not mix)	Its consistency is too low. Consistency changes over time.	Its moisture content is too low; Moisture content changes over time	Mortar is contaminated (Na, Fe) with raw materials, during packaging, by machines
	A	**B**	**C**	**D**	**E**	**F**
2. Man	There are errors in the calculation of the quantity of material to be fed to the mixer and errors in the feeding process (+/- 1 bag)	The mixer is cleaned inadequately by the operator	The raw materials are fed to the mixer too quickly	The operator fails to become familiar with the instruction manual, working “according to his own method”	Incorrect material taken to production (wrong material B or G)	
3. Machine	Mixing is not intensive enough (a ribbon mixer vs. a paddle mixer or any other mixer)	There is limited access to the inside of the machine and limited possibility of cleaning	The mixer paddles rotate during unloading operations (additional mixing and heating)	The raw materials leak from the machine, gaskets are worn or inadequate	The mineral oils used for machine greasing are entering the mixer chamber and contaminating mortar	
4. Method of production	The raw materials are fed manually to the mixer; the repeatability of the feeding pace depends on the operator	The raw materials are fed manually to the mixer; the repeatability of the quantities of the raw materials depends on the operator	The amount of water fed automatically to the system is too large / too small (the operator's reflex; turn the water pump on/off)	Labels are stuck on buckets before unloading operations (production for stock)	The work method is not precise, and the instructions are not clear	Incomplete pallets are filled with buckets containing the product from the previous production batch, only freshly packed pallets are reported
5. Measure-ment	The measurement of consistency is encumbered with errors >30% GRR	The measurement of moisture content is encumbered with errors >30% GRR	The measurement of the content of fraction <63um is encumbered with errors >30% GRR	There are no scales at the raw material feeding station; the raw materials are measured in bags	Data collected during production operations and inspections are insufficient	The water flow meter calibration failed and water content is inaccurate; The Na-Si scale failure

Cont. table 1.

6. Management	Non-compliant products are returned (non-compliant hard mortar is added to fresh mortar)	There is no induction training system put in place 'on-the-job training' for new employees	Cleaning water is used for production purposes instead of being disposed of (it contaminates the system)	Errors are made with respect to the quantity of additives because of changes in the volume of the mixer charge.	There is no organizational culture of "respect for the product"; workers walk on buckets filled with the product (where max load is <72kg)	There is not enough storage space; pallets are arranged in stacks and in consequence buckets filled with the product get squashed or lose their integrity
7. Mother nature	Water is warmer in the summer, colder in the winter. This influences the length of time necessary for the equal dissolution of the components	The mixer tank is warmer in the summer, colder in the winter. The mixer tank is colder during the first shift on Mondays (weekend downtime)	The raw materials are warmer in the summer, colder in the winter. This influences the length of time necessary for the dissolution of the components and the temperature of mortar	The temperature and moisture content in the raw materials warehouse depend on the season of the year	The temperature and moisture content in the production area depend on the season of the year	

Note: numbers 1-7 are indicating 7M groups. Letters A-L are describing subgroup identified within 7M group. Source: The authors' work based on their own sources.

Gathering the identified potential root causes of the problem in one table or presenting them by means of a graphic representation was aimed at restricting the scope of the search to the most probable causes.

This was followed by a GRR study of the measurement system. This is the necessary stage before conducting a data analysis or introducing changes in the process (Kieć, 2018, p. 111). Measurement variability may generate measuring errors that distort the true picture of the situation. The superior task of a measurement system is representing the variability of a selected product feature. Besides variability in a product, a defective measurement system will also show the variability of the environment, a gauge, an operator measuring a particular feature, as well as the feature of the method described in the measurement taking instructions. If a root cause analysis is to result in carrying out corrective actions and assessing their effectiveness, a defective measurement system will generate a false identification of such actions, thus lowering their eventual effectiveness. Table 2 constitutes a summary of the results of the conducted GRR study of the measurable key qualities of the product as described in Table 1. GRR results were measured with application of the statistical software MiniTab, where Total GRR represents total error size coming from the measurement system in reference to PV – process variation, meaning natural process variation measured via standard deviation.

Table 2.

A summary of the results of the GRR study of the measurable key qualities of the product/process

Measurable feature of product/process	Tolerance limits	GRR results: Total GRR Repeatability Reproducibility	NDC: Number of distinct categories	Product to product variability [%]	Measurement system acceptance status
Soft/hard mortar, manual test "go/ no-go"	Hard/soft	No study results	No data	No data	No data
Consistency within limits 200-210 [mm-1]	15 mm-1	Total GRR=87.4% Total GRR=43.5% (for PV=5.0) Repeatability = 87.4% Reproducibility = 0%	10	98.1	No acceptance with respect to the tolerance limits and natural variability in the process
Moisture content within limits 14.5-16.0 [%]	1.5 %	Total GRR=43.8% Total GRR=26.8% (for PV=0.4) Repeatability = 43.8% Reproducibility = 0%	7	96.6	No acceptance with respect to the tolerance limits with the width of 1.5%. Acceptable with respect to natural variability in the process
Content of fraction <63um within limits 54-70 [%]	26 %	Total GRR=13.3% Total GRR=3.6% (for PV=2.7) Repeatability = 13.3% Reproducibility = 0%	9	98.0	Acceptance for the measurement system
The weights of the raw materials	K; G; B: +/-1kg, P: +/-0.1kg	No study results	No data	No data	No data
The weights of water	+/-1 litre	No study results	No data	No data	No data
Measurement system acceptance criteria	Customer's specification	Total GRR <30% Total GRR<10% - world-class	Minimum 5	Minimum 98%	Acceptance for the measurement system

Note. PV – process variation, measured via standard deviation. Source: The authors' work based on their own sources.

The above results of the GRR study indicate that only an examination of the content of fine fractions <63 μm allows the achievement of a reliable measurement result. An examination of consistency and moisture content is characterized by a measurement error described as Total GRR>30%. This error is attributable mainly to the component of "repeatability", i.e. to the measuring instrument, but it can also be related to the lack of repeatability of the sample prepared for the examination. An error in the parameter of "repeatability" is difficult to correct, especially in qualitative tests based on destructive testing in which a sample can no longer be used after a test and its shape, physical state, temperature, etc. is not the same as before a test. GRR for the primary feature of "mortar softness/hardness" has not been measured yet; similarly, there are no GRR results for the weights of the dry raw materials and water fed into the system. Consequently, it cannot be ruled out that the defective (encumbered with considerable errors) measurement system is the cause of a lack of or lower detectability of wet mortar flaws concerning the accuracy of feeding all components of the recipe, as well as the consistency, moisture content, and hardness/softness of mortar.

In view of the above, this should be the end of this paper as there is no possibility of providing reliable data. While the efficiency of the manufacturing processes, safety, or ergonomics can be improved during the real time of process observation by eliminating the causes of a decrease in these parameters, the parameter of quality is not so easy to deal with. Therefore, the most important action to be implemented at the beginning of the improvement process is repairing measurement systems in a manner allowing collected data to be analysed and used in the formulation of true conclusions. Another disadvantage of the current situation is that even if the measurement system is properly repaired, some time will have to pass before there are enough reliable data in the databases. However, a long period of waiting for reliable data was unacceptable because of the high costs incurred by the company. Therefore, additional actions were undertaken; namely, in order to identify the causes of lower product quality it was assumed that it would be satisfactory to identify an "approximate" root cause or that the collected data came from an approved measurement system for which Total GRR was below <<30%. This made it possible to go on to the identification of the causes of the problem in question. A root cause analysis does not consist in identifying and judging those responsible for a problem on the basis of commonly held opinions. It is more like a court trial in which the task is to prove the guilt or innocence of the defendant referred to mathematically as "X". The work team play the roles of the defence counsel or the prosecutor and, using all available qualitative tools, try to conduct an investigation and prove whether the defendant "X" has influence on the consequences "Y". A root cause analysis comprises the formulation of hypotheses and attempts to prove or to disprove them. In calculating the so-called "p-value", one determines the probability of the influence of the examined factor (X) on the end parameters of the product (Y). If p-value > 0.05, then it is impossible to reject the null hypothesis Ho according to which "our defendant X" is innocent. In other words, for p-value > 0.05, the probability that the factor X influences the finished product parameter Y is too low to be regarded as significant. On the other hand, if p-value < 0.05, one cannot reject the alternative hypotheses Ha according to which "the defendant X" is guilty, i.e. the probability that the factor X influences the examined product feature Y will be significant and will exceed 95%.

If application of statistical approach was not possible due to limited time or resources, minor experiments were made, as presented in Figure 2 (below). In order to identify size of potential problems related with not respecting the formulation requirements and weighing tolerances, the following experiment had been performed: addition of too large and too small amount of major recipe ingredient: K, G, B, and more ingredient P, and substitution of ingredient B and G with other, "wrong" material not included in formulation, but with similar appearance.

As presented in Figure 2, the biggest weighing accuracy impact on wet mortar consistency comes from the addition of ingredient B and G, and with this respect, better dosing accuracy should be recommended for manufacturing. Addition of more material P is then required, and substitution of material B with wrong material, can lead to a significant decrease of consistency mean value.

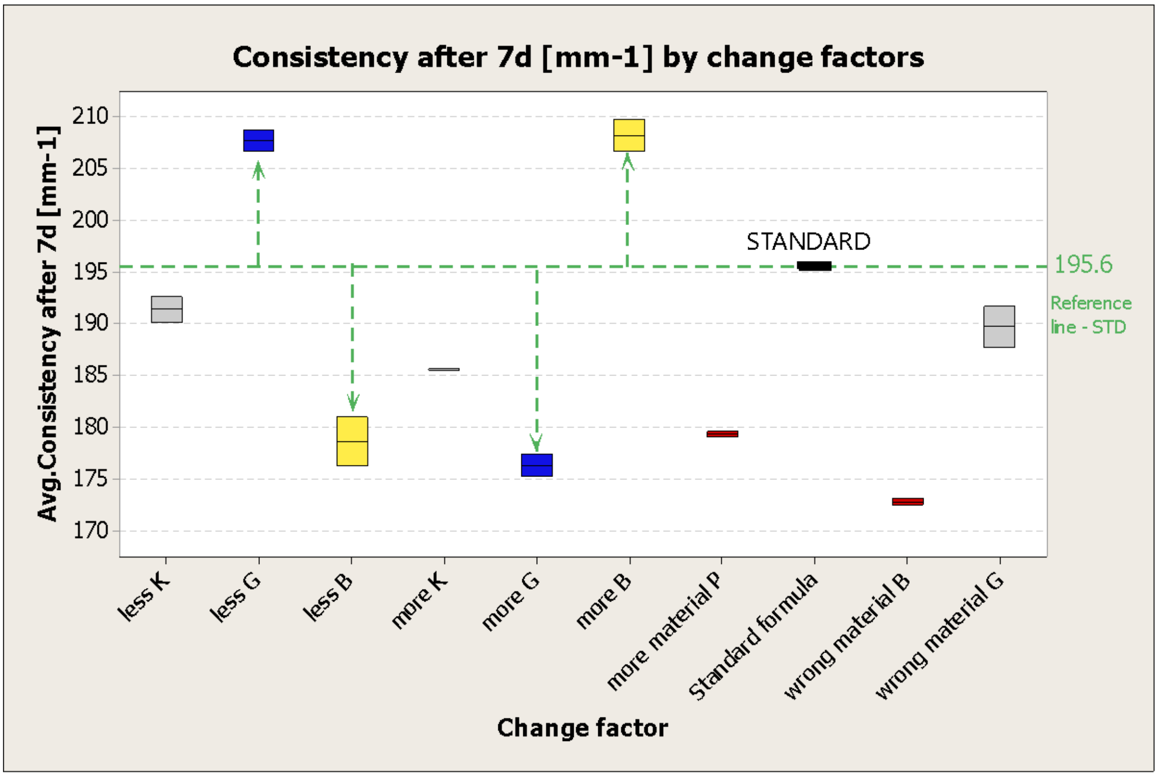


Figure 2. Graphical explanation of not respecting the wet mortar formula accuracy and its impact on mortar consistency. Source: The authors' work based on their own sources.

In order to identify the most probable cause or group of causes influencing the finished product parameter Y, one should carry out tests and describe them statistically. Hence, a plan of statistical tests to confirm the influence of a factor on the loss of the product primary function was conducted and presented in Table 3 below. Where statistically representative amounts of data was not available for analysis, a laboratory experiment was planned in order to confirm/reject root cause likelihood. Some of the parameters not being measured by the available industrial laboratory or not measurable due to some other reasons were characterised as "it may be influence" root cause, and can be analysed in the future.

Table 3.
A plan of statistical tests to confirm the influence of a factor on the loss of a primary function

"Y" – a critical product feature /loss of the product primary function/: **The mortar is hard**			
#	**Category 7M**	**X – a product/process feature**	**The influence of the factor X on the hardening of mortar is confirmed statistically or empirically**
1	1-A	The material G is too fine (outside the specification)	The fines content <0.09 mm (in the examined range (99.75%-100.00%) **does not influence** mortar hardening p-value=0.718
		The material G is added in too large/small quantity	Checked in: 2-A below

Cont. table 2.

2	1-B	In the material K, the specific surface area of grains is too small.	It may influence: Only two results are available 2012=676.803 cm2/g, no cases of hardening 2018=304.808 cm2/g, 9 cases of hardening
		The porosity of the material K is too high	The porosity of grains in the material K **influences** hardening, p-value=0.009 Hard at porosity: x-bar: 4.2027, std.dev: 0.4735 Soft at porosity: x-bar: 3.8957, std.dev: 0.6696
		The density of the material K is too low	Grain density below <0.045mm **does not influence** hardening, in the examined range, p-value=0.567
		The material K is too dusty <0.045 mm	The number of grains **does not influence** hardening, in the examined range (15.1÷36.1%), p-value=0.164
		The material K is added in too large/small quantity	Checked in: 2-A below
3	1-C	In the material B, the Na:Si ratio is <2.05 Solubility in water depends on temperature T=10°C, T=15°C, T=20°C	*No data* It may influence
		The material B is added in too large/small quantity	Checked in: 2-A below
4	1-D	The material P: too large in addition, Solubility in water depends on temperature T=10°C, T=15°C, T=20°C	*No data* It may influence
5	1-E	Water is too cold for all components to dissolve in it (an indirect proof in the 7M category no. 1-C and 1-D)	Checked in: 1-C and 1-D above It may influence
6	1-F	Non-airtight plastic buckets or buckets /exposure to air/ with low resistance to pressure	No data (the parameter is not covered by incoming inspections) It may influence
7	1-G	Depending on an increased content of the dusty fraction <63 um in the mortar	The content of the fraction <63um **does not influence** mortar hardening, in the examined range (+/-5%), p-Value=0.565
8	1-H	Finished product: it is too hot during unloading operations (>30°C)	The temperature of the mix during unloading operations **does not influence** mortar hardening, in the examined range (19.5°C÷43.2°C), p-value=0.348
9	1-I	The raw material is moist and lumped (it will not mix)	No data It may influence
10	1-J	Depending on consistency measurement results	The consistency of the mix during unloading operations **does not influence** mortar hardening, in the examined range (194.4÷227.2 mm-1), p-value=0.274
11	1-K	Depending on moisture content measurement results	The moisture content of the mix during unloading operations **does not influence** mortar hardening, in the examined range (13.9%÷15.7%), p-value=0.521
12	1-L	Mortar is contaminated (Na, Fe) with raw materials, packaging, by machines	No data. Contamination (Na,Fe) may influence mortar hardening Contamination with sealing paste used in the mixer **does not influence** mortar hardening (experimental test)

Cont. table 2.

13	2-A	There are errors in the calculation of the quantity of material to be fed to the mixer and errors in the feeding process (+/- 1 bag). Material K, B, G, P added in bigger/smaller amount, than required	The addition/subtraction of 1 bag of the raw material G or B and a larger quantity of the raw material P **influence** mortar consistency decrease and hardening. The addition/subtraction of 1 bag of the raw material K, influences mortar's consistency with less significance then material G and B.
14	2-B	There are errors in the calculation of the quantity of material to be fed to the mixer and errors in the feeding process (+/- 1 bag)	Checked in: 2-A **does not influence**
15	2-C	The raw materials are fed to the mixer too quickly	No data It may influence
16	2-E	Incorrect material taken to production (wrong material B or G)	Incorrect material B used for production **influence** mortar consistency decrease and hardening.
17	3-A	Mixing is not intensive enough (a ribbon mixer vs. a paddle mixer)	Mixer type **influences** mortar hardening. A ribbon mixer generates 28.6% of hard mortars, while a paddle mixer –5.0%, p-value=0.059
18	3-C	The mixer paddles rotate during unloading operations (additional mixing and heating of the mortar)	When the mortar is being unloaded from the mixer it warms from 25.5°C at 50 kg to 25.7°C at 2000 kg, but the temperature of the mortar **does not influence** its hardening within testing range
19	4-C	The amount of water fed automatically to the system is too large / too small (the operator's reflex; turn the water pump on/off)	No data concerning the influence of this factor on mortar hardening. The quantity of water fed to the mixer **influences** the consistency, moisture content, and temperature of the mortar
20	4-F	Incomplete pallets are filled with buckets containing the product from previous production batches, only freshly packed pallets are reported	The addition of "hard" and non-reported remains from previous production batches **influences** the non-detectability of faults
21	5-A	The measurement of consistency is encumbered with errors >30% GRR	Consistency measurements are encumbered with errors, which *may influence* the non-detectability of faults (GRR=87.4%)
22	5-B	The measurement of moisture content is encumbered with errors >30% GRR	Moisture content measurements are encumbered with errors, which *may influence* the non-detectability of faults (GRR=43.8%)
23	5-C	The measurement of the content of fraction <63um is encumbered with errors >30% GRR	The measurement of the content of fraction <63um is not encumbered with errors and the level of this fraction in the examined range (51.6%÷61.9%) **does not influence** the non-detectability of faults (GRR=13.3%)
24	5-D	There are no scales at the raw material feeding station; the raw materials are measured in bags	Checked in: 2-B above **does not influence**
25	6-A	Non-compliant products are returned (non-compliant hard mortar is added to fresh mortar)	Returned mortar of a very low consistency (the beginnings of hardening) **influences** the hardening of the whole mixture (Chi-Sq, p-value = 0.002)
26	6-C	Cleaning water is used for production purposes instead of being disposed of (it contaminates the system)	Cleaning water used as a recipe component **influences** the hardening of the whole mixture (Ch-Sq, p-value = 0.000)

Cont. table 2.

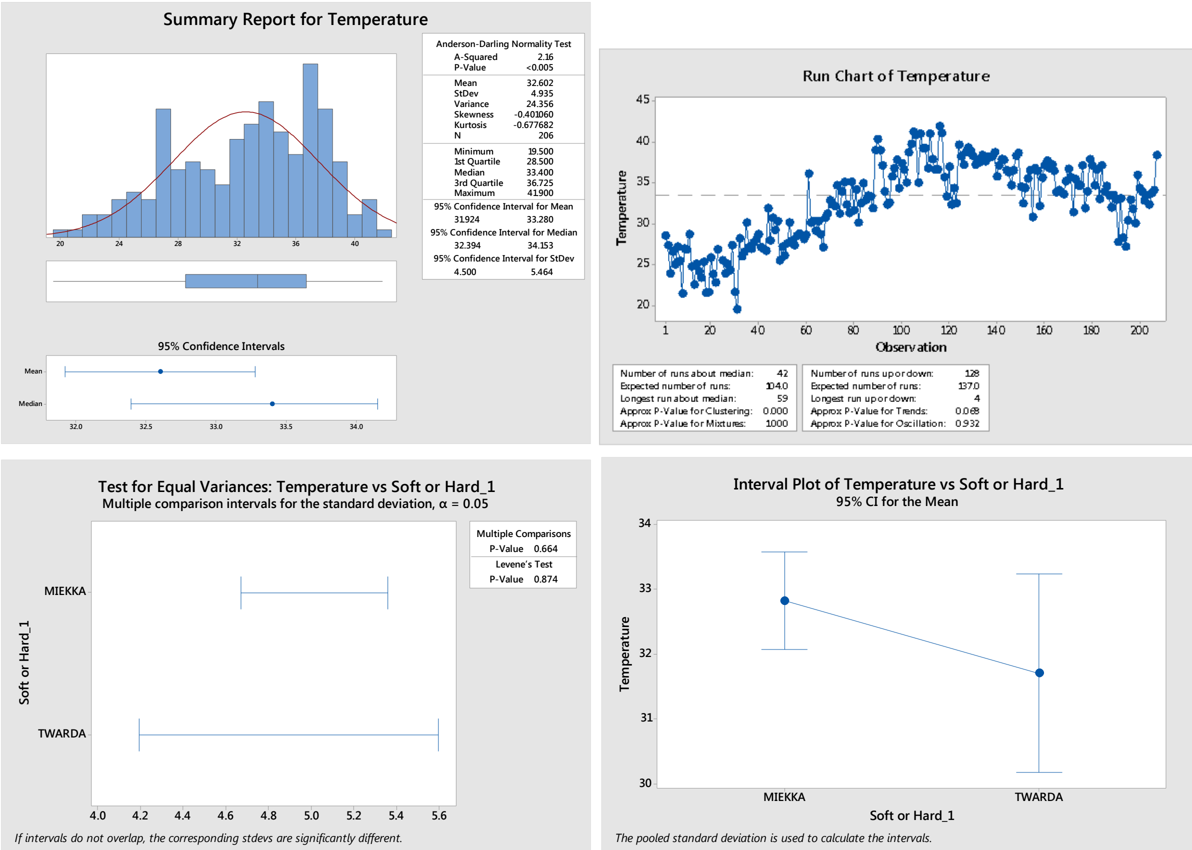
27	6-D	There is no organizational culture of "respect for the product"; workers walk on buckets filled with the product	No data, but *influence is possible*; the maximum load on a bucket is <72kg.
28	6-E	There is not enough storage space; pallets are arranged in stacks and in consequence buckets filled with the product get squashed or lose their integrity	No data, but *influence is possible*; the maximum load on a bucket is <72kg.
29	7-A	Water is warmer in the summer, colder in the winter. This influences the time of dissolution	Checked with experiment. Water temperature is **influencing** mortar hardening
30	7-B	The mixer tank is warmer in the summer, colder in the winter. The mixer tank is colder during the first shift on Mondays (weekend downtime)	Checked in: 1-C, 1-D above It may influence
31	7-C	The raw materials are warmer in the summer, colder in the winter. This influences the length of time necessary for the dissolution of the components and the temperature of mortar	Checked in: 1-C, 1-D It may influence

Note. **influences** were marked in green, **does not influence** were marked in red, and It may influence were marked in blue. Source: The authors' work based on their own sources.

An example of the course of a statistical analysis aimed at confirming that the factor 1-H, i.e. that the temperature of the mortar during unloading operations does not influence mortar hardening or the loss of its primary function, is presented in Figure 3 below.

Mix temperature [‘C] impact was assessed with basic statistical tools, such like: Run chart, Summary Report, Test of equal variances, Analysis of variance and I-MR chart are available with application of MiniTab software. The I-MR chart confirms that mix temperature is not statistically stable, and parameter is statistically "out of control" every time, where trend line (blue line on Figure 2) is crossing upper (UCL) or lower (LCL) control limit (red points). However, UCL and LCL limits are drawn automatically by the calculation of the data distribution central line and 3 standard deviations above and below the central line, and are not limits in the meaning of process parameters.

Analysis of variance is not confirming that in analysed temperature range of 19.5÷40.9 [ºC] is direct a root cause of mortar hardening, because probability described by p-value is >> 0,05. It is also noticeable that clustering impacts temperature. This could be result of seasonability and differences between temperatures of summer and winter seasons.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Soft or Hard_1	1	40.16	40.16	1.65	0.200
Error	204	4952.80	24.28		
Total	205	4992.96			

Means

Soft or Hard_1	N	Mean	StDev	95% CI
MIEKKA	166	32.819	4.974	(32.065, 33.573)
TWARDA	40	31.702	4.725	(30.166, 33.239)

Pooled StDev = 4.92732

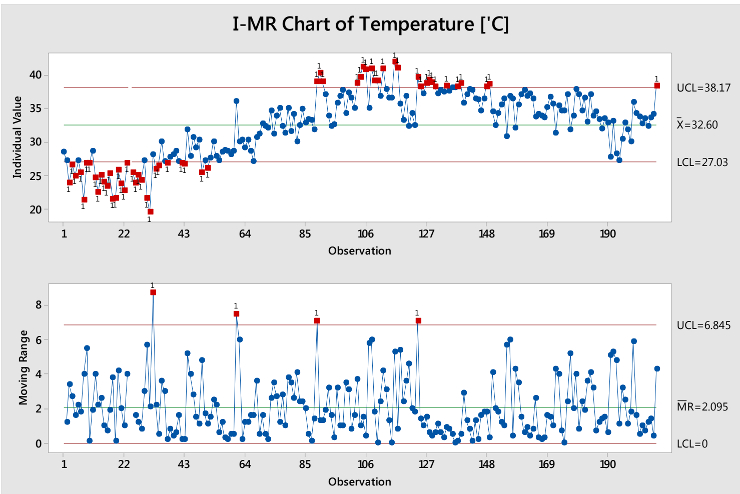


Figure 3. An assessment of the influence of the mortar temperature on mortar hardening. Source: The authors' work based on their own sources.

An assessment of the influence of each factor will consist in verifying the normality of the distribution, examining the stability of the run ("run chart"), and analysing the ANOVA variability with respect to mean and standard deviation. The mortar temperature is characterized by a distribution other than normal, which proves the existence of so-called "special" external factors influencing temperature variability. In the example above, such factor can be the temperatures of the surrounding area, the mixer, and the raw materials – which all depends on the season of the year. The process is not stable and the data create groups and clusters that can also be determined by some external factor, e.g. one production shift, one operator, or one delivery of a raw material. The factors that influence the normality and stability of the distribution should, therefore, be identified and eliminated. An ANOVA analysis allows a precise determination of the influence of a particular factor on a feature under examination, in this case, the influence of temperature and its dispersion (in the examined range of 19.5°C ÷ 43.2°C) on the hardening of the mortar. As the character of the data is other than normal, one uses the result of Levense's test and concludes that the factor under examination has no influence on mortar hardening because the probability level is too low (p-value >> 0.05) and such influence may be regarded as of little significance.

An example of the course of a statistical analysis aimed at confirming the influence of the factor 6-A, that is checking whether returning non-compliant products to the process (the addition of the non-compliant/hardened mortar to the fresh mortar) influences the final quality of the product, is presented in Figure 4 below.

Chi-Square Goodness-of-Fit Test for Observed Counts in Variable: Hard Mortars

```
Using category names in Soft Mortars


                         Test             Contribution
Category  Observed  Proportion  Expected     to Chi-Sq
90              29         0,5      19,5       4,62821
38              10         0,5      19,5       4,62821


 N  DF   Chi-Sq  P-Value
39   1  9,25641    0,002
```

Data groups	Hard Mortars	Soft Mortars
without return of the non-compliant mortar	29	90
with return of the non-compliant mortar	10	38

Figure 4. An assessment of the influence of the return of the non-compliant mortar to the process on mortar hardening Source: The authors' own work based on their own sources.

In analysing the discrete data, one can use the Chi-Square Goodness-of-Fit Test, which will allow one to determine the probability of the influence of one discrete feature (e.g. an additive/ no additive) on the other discrete feature (e.g. soft/hard). The analysis results show that one feature influences the other with the probability p-value = 0.002.

The root causes of quality deterioration: Summing up all analysis results collected so far, one can conclude that there are seven probable root causes of the hardening of the mortar and the loss of its primary functions – which are presented in Table 4 below.

Table 4.
A ranking of the probable root causes of mortar hardening according to p-value score

A ranking of the probable root causes according to "p-value" probability.		
#	**Influence on the occurrence of a fault:**	p-value
1	Using cleaning water as a recipe component influences the hardening of the whole mixture	Chi-Square p-value=0.000
2	The returned mortar of a very low consistency (the beginnings of hardening) influences the hardening of the whole mixture	Chi-Square p-value=0.002
3	The porosity of grains in the material K influences mortar hardening Hard mortar at porosity: x-bar: 4.2027, std.dev: 0.4735 Soft mortar at porosity: x-bar: 3.8957, std.dev: 0.6696	p-value=0.009

Cont. table 3.

4	Mixer type influences mortar hardening. The ribbon mixer #2 generates 28.6% of hard mixes, while the paddle mixer #5 generates 5.0% of hard mixes	p-value=0.059
5	The amount of water fed automatically to the system is too large / too small (depending on the operator's reflex; turn the water pump on/off)	Proved with experiment
6	Only full packed pallets are reported with the manufacturing date of the full pallet. There are in the stock incomplete pallets filled with buckets containing the product from previous production batches, older manufacturing dates.	Proved with experiment
7	Water is not temperature controlled: warmer in the summer, colder in the winter. Cold media increases time of dissolution and may lead to hardening.	Proved with experiment
8	The weighing inaccuracy of the raw materials G or B and a larger quantity of the raw material P influence mortar consistency and hardening.	Proved with experiment
9	Incorrect material B used for production influence mortar consistency decrease and hardening.	Proved with experiment

Note. Source: The authors' work based on their own sources.

There is still long list of "it may influence" root causes that should be investigated in order to complete the study. A plan of major corrective actions based on most probable root causes of the mortar hardening problem, listed in Table 4 above is presented in Table 5 below.

Table 5.
A plan of the major corrective actions

#	*Root cause*	*Action*	*Who*	*When*
1	Using cleaning water as a recipe component influences the hardening of the whole mixture	After the mixer cleaning procedure, used water has to be allocated for disposal.	J.N.	June 2017
2	The returned mortar of a very low consistency (the beginnings of hardening) influences the hardening of the whole mixture	The non-compliant mortar has to be regarded as waste and allocated for disposal.	J.N.	April 2017
3	The porosity of grains in the material K influences mortar hardening Hard mortar at porosity: x-bar: 4.2027, std.dev: 0.4735 Soft mortar at porosity: x-bar: 3.8957, std.dev: 0.6696	Filing a complaint with the supplier. Arranging a meeting with the supplier to clarify the nature of the problem. Changing the raw material specification with respect to porosity	M.K.	September 2018
4	A mixer type influences mortar hardening. The ribbon mixer #2 generates 28.6% of hard mixes, while the paddle mixer #5 generates 5.0% of hard mixes	Transferring the production operations from the ribbon mixer #2 to the paddle mixer #5.	D.R.	August 2017
5	The addition of "hard" and non-reported remains from previous production batches influences the non-detectability of faults	Changing the packing instruction and taking into consideration the necessity of reporting the final parts of production batches in order to improve the identification of all manufactured mortars	D.R.	December 2017
6	Incomplete pallets are filled with buckets containing the product from previous production batches, only freshly packed pallets are reported	Report not full pallets. Enable IT option to fill the not full pallet and assure traceability	D.R.	February 2018

Cont. table 5.

7	The amount of water fed automatically to the system is too large / too small (the operator's reflex; turn the water pump on/off)	Move water amount display in front of the dosing station & operator. Install HMI device where Operator could select recipe and required amount of water will be add automatically. Increase frequency of water flow meter checks.	D.B.	March 2018
8	Water is warmer in the summer, colder in the winter. This influences the time of dissolution	Install pre heating tank, in order to maintain water temperature between 18-22C	D.B.	April 2019
9	The raw materials are warmer in the summer, colder in the winter. This influences the length of time necessary for the dissolution of the components and the temperature of mortar	Install preheating chamber for the raw materials.	D.Z.	April 2019
10	Non-airtight plastic buckets or buckets /exposure to air/ with low resistance to pressure	Improve design of the buckets (from PP to HDPP) and add seal on lid cover to improve air-tightness	M.K./ L.P.	April 2019
11	Confirming / disproving unidentified root causes	Planning tests aimed at determining the p-value probability and improving the defective measuring systems	Team	To be determined at a team meeting
12	Inaccurate content of ingredients B & G in formulation. Incorrect material used for production	Increase of manufacturing line capacity. Automatic batching of powder materials with accuracy of +/-1kg (Big-bags) and +/-0.5kg (25kg bags). Traceability of products and application of bar code system to prevent human type errors.	Project Team	August 2019

Note. The authors' work based on their own sources.

An assessment of the effectiveness of the actions presented in Table 5 above takes place after the implementation of all planned corrective and preventive actions. Such an assessment was based on the comparison of the values of the quality metrics identified on the SIPOC map (Figure 1) and established before and after the implementation of the improvement actions.

Table 6.

An assessment of the effectiveness of the corrective actions

Quality metrics (“outlets from the SIPOC map)	*Before corrective actions (until December 2017)*	*After corrective actions (from January 2018)*	*Value p-value/ comment*
Wet mortar with output parameters consistent with the product specification	Range of consistency: x-bar=209.4 [mm-1] std.dev=5.42 Range of moisture content: x-bar=14.86 [%] std.dev=0.415 Fine fraction <0.063 mm content in the mortar x-bar=57.01 [%] std.dev=2.75	Range of consistency: x-bar=222.77 [mm-1] std.dev=14.04 Range of moisture content: x-bar=13.98 [%] std.dev=0.513 Fine fraction <0.063 mm content in the mortar x-bar= 56.08 [%] std.dev= 1.861	p-value=0.000 p-value=0.000 p-value=0.077

Cont. table 6.

Soft mortar 24 hours and 7 days after the date of manufacture and during 12 months after the date of manufacture % of waste at the established level <1%	Quantity of non-compliant hard mortars 23.5 [%] after go/no-go test	Quantity of non-compliant hard mortars 4.4 [%]	p-value=0.002
Mortar is packed in airtight containers, labelled and properly stored in the warehouse	No metric	(Still) no metric	No data, but series of experiments with improved lid sealing are already confirmed by Customer as efficient
No repeatable complaints	Number of complaints about hard mortar **13** [pcs.] Number of repeatable complaints **9** [pcs.] - according to the date of manufacture of faulty mortar	Number of complaints about hard mortar **2** [pcs.] Number of repeatable complaints **1** [pcs.] - according to the date of manufacture of faulty mortar	The objective of “no repeatable complaints” was not achieved, but in 2018 the company received 11 complaints fewer (including 8 repeatable complaints fewer)

Note. Source: the authors’ work based on their own sources.

Conclusions

Manufacturing of wet refractory mortar is a challenging task, especially in a variable industrial environment and the application of naturally sourced raw materials. However, after the implementation of the corrective actions, the company managed to lower the volume of non-compliant wet mortars from 20.7% (2017) to 4.4% (2018) and to 3.6% (S1:2019), which allowed it to reduce manufacturing costs. Reduction of the overall rejection rate was obtained after successful introduction of “A plan of major corrective actions”, listed in Table 5 above.

Nevertheless, this volume is still above the target level of <1%. The number of repeatable complaints improved and fell from 9 in 2017 to 1 in 2018. When the corrective actions had been introduced, there occurred significant ($p\text{-value} < 0.05$) changes in mortar consistency and moisture content. During the course of the root cause analysis the team acquired considerable knowledge of the wet mortar manufacturing process, the quality control process, customer requirements, and potential causes. The collected data and information may be used in a subsequent assessment of effectiveness after the verification of the still unconfirmed causes and the implementation of further improvement actions.

It is not a rare occurrence that a particular problem resurfaces despite the appearance that it has already been solved. It should be noted that a root cause is not caused by a single factor. What usually happens is that a set of causes responsible for a defect is detected. A root cause analysis is not about "believing" that a given factor exerts a particular influence, but about following the pragmatic approach, as well as performing observations and coordinated measurable actions which will allow the researcher to examine a larger piece of the iceberg hidden deep under the surface of the water. On the basis of the conducted research, one can conclude that the application of various quality methods and tools in analysing technological processes is useful for the long-term reduction of the costs of bad quality (in contrast to drawing hasty and simplistic conclusions). In the case of technological processes, identifying key process parameters that influence product quality, as well as improving such parameters is an especially difficult task.

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