SCADA Systems and theirs Connection with Statistical Process Control in Foundry

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Abstract

The paper deals with problems of analysis and usability of the SCADA systems (Supervisory Control and Data Acquisition) in the foundry industry. In such complex manufacturing systems, a real-time feedback control of all the sub-processes of the casting process routing is not possible. Parameters of the particular processes may be accumulated in the scattered (directly incoherent) databases. Application of the SCADA modules in the foundry requires a specific approach. In the first place, weights for groups of monitored parameters affecting the process and the casting quality may be defined, on the basis of the engineering knowledge of specialists from the foundry branch. The described problems are a challenge for the foundries also for another reason: periodically performed audits force application of the statistical methods for control of the processes’ stability. On a specific example, the paper presents guidelines for design of the control charts. Also, an example of implementation of the author’s own application of the SCADA type for one process in a cast iron foundry is presented. It was proposed to apply a method devised by the author – RSP (Redesign and Stabilization of Process), used for design of a control chart, taking into account the guidelines contained in a branch standard ISO TS 16949, dedicated to the automotive industry. It is shown on an example of the Xi chart of single observations. It was referred to monitoring of a relatively easy control of temperature of pouring of the casting molds on an automated molding line. It is an important parameter, considering the aspect of influence on the discontinuity defects, having an evident relation with variability of temperature of the metal stream entering the mold. The methodology allows to assess the stability of this process, more precisely – its so-called capability (c_p and c_pk indices) and propositions of procedures of correcting a specification limits of the temperature stream.

Keywords: Application of information technology to the foundry industry, SCADA systems, Data acquisition, Statistical process control (SPC), Shewhart control charts (SCC)

1. Introduction

The SCADA acronym (Supervisory Control and Data Acquisition) does not have to be always understood unequivocally and area of its interpretation is related to a class, complexity level and possibility of control of certain phenomena in a given branch of technology. On the one hand, it is related to elements such as equipment of measuring systems and operational systems for monitoring and control, on the other hand – modules of computer aided operation of the whole SCADA system, including software for data processing subjected to acquisition and transfer of control signals to final elements. For example, bodies of specialists related to industrial automatics (production of Programmable Logic Controllers – PLCs) propose to use a term of “supervision and acquisition of data” [1], while other groups, related to widely defined maintenance and ensuring of manufacturing continuity, define functions of the SCADA systems as “inspection of operation of particular control elements” [2]. The acronym is often referred only to “monitoring and control” [3]. It is apparent,
that in many cases the important function of these systems – effective data acquisition – is not emphasized enough.

According to the literature descriptions, the SCADA systems are a group of applications responsible for controlling the course of the manufacturing process, which allow to information (data) acquisition from particular devices and its visualization, for example in form of time diagrams, set on one axis of time of the main process. An important task of these applications is also recognition of alarming states. In a way, it is somehow a control of the manufacturing processes [4], because when the information about an alarm occurs, an employee uses the SCADA application to correct the process (by controlling the parameters of machines and devices using the off-line method), to obtain planned values of output signals of the machines. Communication of a computer (with the installed SCADA applications) with the mechanism controlling operation of the machines and devices (mostly the PLC controllers) is possible thanks to dedicated drivers, designed for a given device (on-line method). Universal methods and procedures for the computer – machine/device data exchange, such as OPC (Object Linking and Embedding for Process Control) or DDE (Dynamic Data Exchange) are used more and more often [1].

The mentioned group of applications is well suited for managing a group of already automated processes, which, despite high complexity regarding generation of parameters, bring results which are more or less clear and readable for the control systems. Examples of such applications are, among others, energetic and gas industry, sewage-treatment plants, mining and metallurgy [2]. Still, it needs to be emphasized once more, that it usually concerns large area topography of repeatable and multiple identical measurement and control devices (e.g. in a sewage system or energetic system). On the other hand, it may concern important partial processes, from the manufacturing technology point of view, which are taken out of a direct context and then the mentioned examples of applications gain another, isolated and individual meaning. Application of the SCADA type of systems in service of complex processes on example of foundry has been proposed, among other sources, in [4]. Another example may be the Küttner system, introduced in one of the domestic foundries in the last decade of the past century, for control of the long campaign cupolas. Considering the year of implementation, it was an innovative and modern control installation for utilization of warmth of the cupolas' waste gases and their cleaning.

When making an attempt at application of a SCADA type of system, a problem appears in case of trying to relate diversified parameters subjected to acquisition from the processes which are co-responsible for the final casting quality, e.g. a sequence of processes of molding sand preparation or preparation of a liquid casting alloy. In this approach, the final casting quality consists mostly of state of continuity and compactness of structure and mechanical properties. In foundry, still many parameters are collected outside data acquisition systems, including computer systems from the SCADA group, and their recording is performed in a traditional way (manual records on paper). Systems dedicated for foundry are developed only sporadically [5,6] and are met with enthusiasm also by the customers of foundries – it makes them easier to perform the periodical audits. It needs to be emphasized, that a large amount of processes in the foundry and their technical equipment are not adjusted for wide application of programmable controllers, allowing on-line communication and in the near future it will probably be an unprofitable direction, not subjected to development. Anyway, as regards the SCADA systems, there is a certain “green light” for them. Let’s get back to the aforementioned partial processes, seemingly taken out of context of direct relations with the holistically perceived production in a given foundry. One can successfully bet on analysis and control of stability of the most important groups of parameters as factors deciding the final casting quality, according to the weigh ranking justified on basis merit (on the basis of engineering knowledge of specialists).

Another method is a selection of the most important parameters through statistical analysis, with filtering (discarding) of data according to an assumed significance criterion, not showing an influence on a specific quality coefficient [7]. A promising direction is connection between both types of ranking procedures.

A motivating challenge for a foundry can be an audit aimed at assessment of a state of control of the production processes, with application of the SPC (Statistical Process Control) methods for this purpose [5]. Recipients of the castings, most frequently from the automotive branch, are used to methodological stereotypes of the SPC procedures and they expect from a foundry to fit in this kind of procedures.

The paper presents an example of use of the SPC methods in an author’s own system for data acquisition – KMESQ-SPC – which fits in group of the SCADA applications. This tool is integrated with the KMESQ application [6], which is used for collecting and analysis of large and scattered data sets. Both systems have a software structure allowing successive development, with intention of automation of control (adjustment) and monitoring (regular, planned measurement and recording of processes’ parameters).

2. Principles for the formulation conditions reception quality castings

Manufacturing a final product in form of a casting is related to realization of many processes, characterized with diversified degree of complexity and influence on the final quality of the casting. Quality of the casting should meet criteria defined by its recipient – so-called Customer Technical Acceptance Requirements (C-TAR). It is known, that in some manufacturing branches of the machine industry, definition of the product quality and its measurable (quantitative) criteria, because of specificity of – for instance – machining processes, is relatively easy to identify and unequivocal regarding to the limiting values, what is used for SPC procedures.

In case of foundry, where there are many manufacturing processes diversified regarding materials and technology, C-TAR (also expressed quantitatively) have a specific character and are usually negotiated with a designer/recipient in detail. Indirect parameters of foundry manufacturing processes (the most important ones, named main process features should be subjected to effective acquisition and having these growing datasets is a sine qua non condition of approaching the SPC problem) do not interact in an unequivocal and clear way with the final quality
parameters – the influence is rather synergic. This, as presented later, will have an influence on attempts of application of the SPC methods in this situation and translating these actions on the so-called final quality.

Let’s consider an example of manufacturing a body of the compressor out of cast iron, of weight about 15 kg, for the automotive branch. The casting should meet the following requirements regarding:

- mechanical properties, defined on samples cast separately and/or trepanned (Rm, Re, A5, HB) along with material properties (structure, chemical constitution),
- state of continuity (compactness) of the casting structure, with allowance of discontinuities in strictly defined areas of the casting, which are not endangered with a progressing degradation during operating loads (tolerance of damage [8]),
- state of this compactness, which may appear in form of a criterion of leakproofness, for example, and also in form of standardized quality classes requiring detailed control procedures with application of Non-Destructive Testing (NDT) methods [9,10],
- state of the casting at the moment of sending (after preliminary or final processing, cleanness, state of the surface – painting, packing).

Globally understood quality is recorded in form of a specification of the casting features and is most often a document – an attestation, which should describe the product operating functions and should not enter the “super-quality” area, which is costly and irrational. An assumption, that the customer-auditor will not be interested in a way of supervision of the manufacturing processes course in the foundry but only in a quality of the final product, is now a thing of the past. In most cases the customers require the cooperating suppliers to have an implemented quality management system. Standards, which are a base of such a system, allow the processes to be inspected by the customer in form of the external audits (of type C). Therefore, nowadays implemented and effectively used quality control systems, compatible with requirements contained in the ISO 9000 standard series, impose significant restrictions regarding control and inspection of the manufacturing processes. As main aims, they assume, among other things [11]:

- supervision of a product delivered by a supplier,
- identification and identifiability of the product,
- inspection and testings, process control,
- corrective (repairing) and preventive operations.

Complying with these rules is not always an easy task. The standards impose a requirement to supervise the process, but they do not directly indicate ideal, even dedicated tools for particular manufacturing processes [6].

More and more often while receiving the products, customers pay attention not only to suppliers adjusting to procedures of the implemented quality management system, but also to detailed guidelines regarding the technical procedures, defined in the branch standards. In the medicine, aeronautics or the food industry, they have been used for many years. In case of the heavy industry, for example foundry, to meet the customers’ requirements, for instance – car producers, it is necessary to adjust to technical specifications defined in the quality management standard for the automotive sector – ISO/TS 16949 [12,13]. This standard is based on a structure of the ISO standards from the 9001 series, but contains more strict technical supplements of the automotive branch requirements, among other things in field of statistical process control and its documenting, hence the SPC problems appear as parts of audits in companies which produce castings on a weight scale, for example on automated lines.

Monitoring of stability and capability of a process using the statistical tools is called Statistical Process Control (SPC). The most often used SPC tools are control charts and capability indices [14,15]. The control charts allow to react quickly in case of appearance of the special causes influencing the process or changes of character of perturbations resulting from the random causes. The process capability indices allow to determine the capability of the process to meet the imposed requirements regarding the considered features of the product/process at the moment of analysis. The manufacturing process route does not always allow to meet this seemingly obvious condition.

In the further part of the work, the authors analyze if the results obtained through the statistical process control can be considered according to the SPC criteria identical in other production branches. Specificity of the foundry processes causes that this problem worthy of a particular attention.

3. SPC in materially and technologically complex manufacturing processes

Application of the SPC tools can have variable character. In case of materially and technologically complex manufacturing processes, occurring, among other things, in foundry, it is entirely different than in branches, where certain features, such as dimensions (geometrical parameters) of the final product, can be supervised relatively easy. More and more often customers of foundries during audits require implementation or at least adjustment to requirements of the specialized standards. As results from, for instance, the ISO/TS16949 standard, these requirements can be as following: indication of processes which can be controlled and by which parameters, real-time examination of causes of variability in a process, as well as application of methods of a quick detection of incompatibilities of a product/process, to take correcting actions [12-14].

Continuing the “foundry” example, the authors are familiar with cases, where the customer requires supervision and documenting of “evidence” of stability of the manufacturing processes related, for example, to production of the mold sand or metallurgical quality of a liquid alloy. From the foundry viewpoint, these materials are formed during partial processes related to production of the casting. In these processes, out-of-control conditions may occur in a short time period. Often, undetected even by an acquisition system, they do not influence the final casting quality unequivocally and clearly [9,14]. Obviously, it makes the analysis of causes of the faulty products more difficult. The most difficult problem for identification and control in the foundry is minimization of discontinuities in the casting structure (shrinkage and/or gas-shrinkage). Even if they occur, they do not have to disqualify a casting as a product incompatible with the C-TAR. It happens especially when after
machining, no defects are detected in the casting using visual or other NDT methods [9, 10]. This stage and production of the first castings for quality qualification (specimen casting) should be conducted in conditions of a perfect communication between the foundry and the customer [8].

It needs to be emphasized, that unequivocal and universal definition of the final casting quality is practically impossible. It may concern at most a specific assortment. It is always corresponding to the casting receiving conditions and rationally applied rule of tolerance of damage [8]. Unequivocal interpretation of influence of phenomena occurring on stages of the particular intermediate processes related to forming of the casting and their correlation with the final quality is out of the question. In this situation, the authors think that effective application of the SPC methods in foundry is possible, but with application of a modified algorithm, for example regarding to the problem of the control chart design for the selected main features (parameters) of the partial processes according to the manufacturing processes route. In the further part of the paper, proposal of such a methodology will be presented, along with an example of SPC implementation in one of the domestic foundries.

4. Design of control charts for a selected process of inhomogeneous manufacturing structure

Control charts are basic and the most used SPC tool. They are specially drawn diagrams, which contain a centre line (CL), control limits $3\sigma$ (upper/lower control limit $3\sigma - \text{UCL}$, LSL), warning limits $2\sigma$ (upper/lower warning limit $2\sigma - \text{UWL}\_2\sigma$, LWL2$\sigma$) and warning limits $1\sigma$ (upper/lower warning limit $1\sigma - \text{UWL}\_1\sigma$, LWL1$\sigma$) of corresponding values of deviations from the global average $\mu$ of the process: $3\sigma$ (in the range of $\mu \pm 3\sigma$, $99.73\%$ of a value of a given feature is contained), $2\sigma$ (in the range of $\mu \pm 2\sigma$, $95.45\%$ of a value of a given feature is contained), $1\sigma$ (in the range of $\mu \pm 1\sigma$, $68.26\%$ of a value of a given feature is contained) [15]. Designations of $\mu$ and $\sigma$ are an average and a standard deviation of a population, correspondingly. In the diagram, values of statistics related to a supervised parameter of a process (e.g. average values, standard deviations or single values) are plotted in a function of time. Idea of structure of a control chart is shown in the Figure 1.

The control charts are most often used in various manufacturing branches, including foundry [14, 16]. Independently on the place of their application, it is assumed that variability of the process may have a random character or may result from special causes. The special perturbations appearing in the process are identified on the basis of so-called patterns of out-of-control process. There are many of them, as shown in [17]. The most important of them are considered (compare with the Figure 2):

- A: one point outside the A zone,
- B: fifteen subsequent points in the C zone above or below the central line,
- C: nine subsequent points in the C zone or outside of it on the same side of the central line,
- D: six subsequent points of successively increasing or decreasing values,
- E: fourteen subsequent points alternately increasing and decreasing (points may be contained in all the zones alternately).

Fig. 1. Idea of structure of a Shewhart control chart (own work)

The control charts may describe features evaluated using the alternative method (also known in literature as the attribute method) pertaining to non-measurable values or a numerical one (measurable values). In case of the manufacturing processes, the numerical evaluation is the most common in applications. The paper focuses on this method of evaluation. Designing the control charts for numerically evaluated features, independently on the manufacturing specificity, should be carried out in 3 stages [15]:

- selection of design method for the control chart,
- selection of the pilot trial,
- estimation of parameters of the control chart.

The first stage of design of a control chart is related to selection of method of the chart design [6, 19]. Two methods are generally used: the stabilization and the design method. The first one is based on data collected from the already running process (already existing processes, where the controlling limits are calculated on the basis of data collected during the process in defined time intervals), while the second one is used where obtaining data from the process is not possible. The latter is used
mostly for unexplored processes, where a basis for calculation of the control limits is application of appropriate preliminary assumptions regarding the tolerance (specification) limits of an analyzed parameter of the process or Cp and Cpk indices [19]. In practice, the stabilization design of the control chart is the most frequently used method.

In the next stage, values of the measured feature are recorded for a so-called pilot trial, which means that it is taken from a process which is statistically adjusted (only random causes appearing) and performed in close to ideal conditions. On that basis, control limits are determined [20]. During the stage of estimation of the control limits and calculation of the process capability indices, it is important to base on complete and reliable data about the processes continuity. It can be ensured, for example, by a system for the data acquisition integrated with the analyzed process. The authors have described this topic in several works, the most important being [5,21,22]. A very important problem is, along with completeness of the databases, constant supervision of updating algorithms of their acquisition [14].

Table 1. General characteristics of the data recorded in the A&DM databases [5] corresponding to the parameters of the control chart

<table>
<thead>
<tr>
<th>CUMULATIVE DATA</th>
<th>May, 5 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poured castings</td>
<td>1980 pcs. (to 4 pcs per mould)</td>
</tr>
<tr>
<td>Weight of the casting net/gross</td>
<td>approx. 15 kg / 23 kg</td>
</tr>
<tr>
<td>Number of defective castings (def. 206 and 404)*</td>
<td>250 pcs.</td>
</tr>
<tr>
<td>Percentage of defective castings (def. 206 and 404)*</td>
<td>12.63 %</td>
</tr>
</tbody>
</table>

**DATA FROM THE A&DM COMPUTER SYSTEM – POURING & QUALITY BASE**

<table>
<thead>
<tr>
<th>Number of poured castings</th>
<th>Weight of poured castings</th>
<th>Type of the defect</th>
<th>Number of defective castings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050</td>
<td>13.950 kg</td>
<td>W206</td>
<td>160</td>
</tr>
<tr>
<td>930</td>
<td>15.3750 kg</td>
<td>W404</td>
<td>90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time interval of mold pouring</th>
<th>Average pouring time[s]</th>
<th>Average pouring temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:35-13:50</td>
<td>12.5</td>
<td>1349</td>
</tr>
</tbody>
</table>

*) W206 – defect called "sking piping", W404 – defect called "shrinkage porosity" **) because of a large number of data records (several hundred), only average values are shown, coming from the detailed databases.

The table 1 presents data, which approximates preparation of the pilot trial. A parameter which was indicated by the foundry as a potential reason of the greatest quality problems and instability of the faulty products in a series (measurable value fluctuation in a batch of pours) was the pouring temperature (TPOUR). Higher values of the pouring temperature present in the beginning of the series analyzed below (see Figure 3) were caused by identified perturbations in the process of preparation of the cast iron for the casting (according to the SPC nomenclature – special causes).

The pouring temperature, according to the common knowledge, can be a cause of several defects, including W102 defect – short run and shrinkage originating defects: sking piping (W206) and shrinkage porosity (W404) [23]. Indeed, the two last defects (W206 and W404) dominated in summaries of faulty products (along with the W406 defect – sand holes, but their intensity is not affected by the pouring temperature). Because of the W206 and W404 defects, during the stage of the pilot trial design, the TPOUR parameter was selected for control of the pouring process.

5. Research and results

5.1. Data acquisition and preparation of the pilot trial

The study was realized on an example of a foundry manufacturing castings from cast iron, for the automotive industry (the weight of a single raw casting, without the gating system and the head is about 15 kg) on an automated line flaskless with a horizontal mold division [6].

Preparation of the pilot trial and application of the control charts for manufacturing processes control will be shown on an example of implementation of a control chart for a selected process (mold pouring temperature on an automated line) in a cast iron foundry.

5.2. Process capability indices for the pouring process

For assessment of the process capability, the Cp and Cpk indices are the most often used. The Cp index shows how many times the natural process variability fits in the tolerance field (μ±3 sigma). The Cpk index gives consideration to position of the average value of a feature in relation to the tolerance limit. The most beneficial situation for the process occurs when it is centered (Cp=Cpk), with values of both indices much higher than 1. It turned out, that the Cp and Cpk indices were much smaller than 1 for the gathered data. The situation repeated itself also for other periods of the same year. Still, the authors have decided to continue their work in order to show, that on the basis of the methodology shown in the further part of the paper, the values of the process capability indices related to the TPOUR parameter.
lower than one do not influence the increase of number of the faulty products in an unequivocal way. In the next chapter, results of measurements of temperature $T_{POUR}$ are shown, along with an approach to design of the control chart parameters on an example of the batch of castings described earlier, when the process capability indices for a feature selected for monitoring are lower than 1.

The authors have come to a conclusion that in this case, an approach to design of parameters of the control chart must be slightly modified. It was proposed to preliminarily accept $C_p$ and $C_{pk}$ values lower than 1 for the final modified version of the pilot trial. The methodology named RSP in short (Redesign and Stabilization of Process) was applied in an example shown in the table 2. The equations (1) and (2) were used to calculate the process capability indices.

$$C_p = \frac{USL - LSL}{6\sigma}$$  

(1)

$$C_{pk} = \min\{\frac{UCL - x_{av}}{3\sigma} ; \frac{x_{av} - LCL}{3\sigma}\}$$  

(2)

designations:

USL – Upper Specification Limit
LSL – Lower Specification Limit
UCL – Upper Control Limit
LCL – Lower Control Limit

Full description of the RSP methodology algorithm can be found in [24].

5.3. Results – desing of control chart

The results were collected and processed using the software created by the authors (R. Sika, Z. Ignaszak): A&DM (for data acquisition and data mining, implementation preceded the work on the SPC) and A&DM-SPC, implemented for a test period in the foundry during the SPC study. Implementation of the system was preceded with a series of professional trainings for the future users. Introduction of the control chart of single observations $X_i$ was proposed, where single values of a given parameter ($T_{POUR}$) are taken into consideration. For that purpose, the Generation of the pilot trial module of the A&DM-SPC system was used. The module is used for determination of parameters of a control chart on the basis of a pilot trial. Design of the control chart was carried out according to the RSP methodology prepared by the authors, developed on the basis of research work in the preceding period [25,26]. Below, an application of the methodology for the description of the example presented earlier is shown.

After extraction of the $T_{POUR}$ data (463 records), it was visualized (Fig. 3). It was checked if the given feature is compatible with the normal distribution (using the Kolmogorov-Smirnov test). Initial values of $T_{POUR}$ were too high and exceeded the upper tolerance limit by 8-90°C (after identification of the problem, its cause was detected and these values were omitted in the further analysis).

For this uncleaned dataset, the Kolmogorov-Smirnov statistical test resulted in rejection of the hypothesis of the feature distribution approximating normal distribution. Methodology applied in the algorithm of the A&DM-SPC system allowed easy removal of deviating values qualified as errors. Then, the statistical test identical to the first one was conducted and it showed that distribution of the examined parameter can be assumed as the normal distribution. Consequently, preliminarily the cleaned dataset was assumed as the original (initial) pilot trial and it was decided to use it for design of the control chart using the stabilization method.

In the further stage of the control chart design using this method, selected values of the measured feature were removed if it was found that during the measurement one of the special causes appeared (but with an assumption, that the cause of deviation was identified evidently). The control chart designer, after identification of a reliable cause of occurrence of the deviating values, may proceed with the consecutive data cleaning and recording an appropriate commentary in the window of the A&DM-SPC system, (Fig.4 in [6]).

The data removal action can be repeated until the process is found stable. In such a way, idealized picture of reality is created with designer fully aware that elimination of these indicated causes is a challenge for the foundry workshop. The Table 2 presents subsequent steps of generation of the control chart. Relations (3) to (5) show a method of determination of the control limits and the central line.

$$LCLxi = x_{av} - 2.66*MR_{av}$$  

(3)

$$CLxi = x_{av}$$  

(4)

$$UCLxi = x_{av} + 2.66*MR_{av}$$  

(5)

designations:

$x_{av}$ – coordinate of the central line (average from measurements)
$MR_{av}$ – average range from ranges from the two last measurements
POUR a rational action.

Table 2.

<p>| Stages of generation of the Xi control chart of single observations |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|</p>
<table>
<thead>
<tr>
<th><strong>Original sample</strong></th>
<th><strong>n</strong></th>
<th><strong>MIN(n)</strong></th>
<th><strong>MAX(n)</strong></th>
<th>x̄</th>
<th>R</th>
<th>LCLx</th>
<th>UCLx</th>
<th>LCx</th>
<th>σ</th>
<th>C_p</th>
<th>C_pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>463</td>
<td>1312</td>
<td>1440</td>
<td>1348</td>
<td>128</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>13.55</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**STEP 1**

**Data cleaning method**

- Data removal from 2 to 122

<table>
<thead>
<tr>
<th><strong>n</strong></th>
<th><strong>MIN(n)</strong></th>
<th><strong>MAX(n)</strong></th>
<th>x̄</th>
<th>R</th>
<th>LCLx</th>
<th>UCLx</th>
<th>LCx</th>
<th>σ</th>
<th>C_p</th>
<th>C_pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>1312</td>
<td>1375</td>
<td>1340</td>
<td>63</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>11.05</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**STEP 2**

**Data cleaning method**

- Removal of values: TPOUR < 1320 and TPOUR > 1350

<table>
<thead>
<tr>
<th><strong>n</strong></th>
<th><strong>MIN(n)</strong></th>
<th><strong>MAX(n)</strong></th>
<th>x̄</th>
<th>R</th>
<th>LCLx</th>
<th>UCLx</th>
<th>LCx</th>
<th>σ</th>
<th>C_p</th>
<th>C_pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>255</td>
<td>1325</td>
<td>1355</td>
<td>1338</td>
<td>35</td>
<td>1318</td>
<td>1357</td>
<td>1338</td>
<td>7.63</td>
<td>0.705</td>
<td>0.596</td>
</tr>
</tbody>
</table>

**STEP 3**

**Data cleaning method**

- Removal of samples from 40 to 67

<table>
<thead>
<tr>
<th><strong>n</strong></th>
<th><strong>MIN(n)</strong></th>
<th><strong>MAX(n)</strong></th>
<th>x̄</th>
<th>R</th>
<th>LCLx</th>
<th>UCLx</th>
<th>LCx</th>
<th>σ</th>
<th>C_p</th>
<th>C_pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>228</td>
<td>1325</td>
<td>1348</td>
<td>1338</td>
<td>23</td>
<td>1318</td>
<td>1357</td>
<td>1338</td>
<td>7.55</td>
<td>0.720</td>
<td>0.645</td>
</tr>
</tbody>
</table>

**STEP 4**

**Data cleaning method**

- Correction of the tolerance limits, after discussion between Z. Ignaszak and the process engineers

<table>
<thead>
<tr>
<th><strong>n</strong></th>
<th><strong>MIN(n)</strong></th>
<th><strong>MAX(n)</strong></th>
<th>x̄</th>
<th>R</th>
<th>LCLx</th>
<th>UCLx</th>
<th>LCx</th>
<th>σ</th>
<th>C_p</th>
<th>C_pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>1325</td>
<td>1348</td>
<td>1338</td>
<td>23</td>
<td>1318</td>
<td>1357</td>
<td>1338</td>
<td>7.55</td>
<td>1.045</td>
<td>1.015</td>
</tr>
</tbody>
</table>

In the step 3 (after removal of 27 points), final control limits were obtained, with the process capability indices still lower than 1. In this case, it was agreed with the customer (used to a classical SPC approach) that change of limits of the tolerance field will be a rational action.

Constrained interval for TPOUR (from 1320 to 1350°C, tolerance field 30°C) played a role of “policeman” in opinion of the foundry specialists. It psychologically imposed corrections of the service actions to reduce the real dispersion, which was, however, not possible in the most cases in their opinion, for several reasons which will be not mentioned in this paper. At the same time, until the control chart was introduced, no effective statistical tool was used for the on-line stability evaluation (even using the comparative method by service of workplaces, weekday, type of assortment etc.).

In agreement with the process engineer, after analysis of potential influence on the defectiveness of assortments in this foundry due to defects W206 and W404, widen the tolerance field by 5°C downwards and 10°C upwards (TPOUR from 1315 to 1360°C) were proposed. Therefore, new tolerance limits were defined, noted as TPOUR-USL2 and TPOUR-LSL2 (upper and lower specification limit of the pouring temperature, version 2). The previous values were saved in the database (as version one). This change allowed to obtain the process capability indices higher than 1 (see Figure 4).

In the step 2 (after removal of 360 points), the control chart was introduced, no effect of the process capability and not its real improvement of the pouring process stability was achieved, by comparing subsequent pouring series relations (the pilot trial can be or even should be verified and defined for each assortment, especially for the differences regarding weight and shape of the casting). Also, a follow-up monitoring of the TPOUR history from the previous pours was introduced to the system of measurement.

**Fig. 4.** Final diagram of the pilot sample; the diagram presents the central line (continuous line), upper and lower control line (dashed lines) and the tolerance limits (continuous lines)

It is worth to remember that such an action is an artificial increase of the process capability and not its real improvement through minimization of the variability resulting from natural causes. However, it turned out that by this way, expected improvement of the pouring process stability was achieved, by comparing subsequent pouring series relations (the pilot trial can be or even should be verified and defined for each assortment, especially for the differences regarding weight and shape of the casting). Also, a follow-up monitoring of the TPOUR history from the previous pours was introduced to the system of measurement.
and recording of the $T_{POUR}$ temperature. This approach, along with the A&DM-SPC system, has started to bring improvement of the process stability.

6. Summary

The paper refers to control of the manufacturing processes in foundry with aid of systems belonging to the SCADA group. Application of a system of this group in foundry requires a special approach. In the SCADA solutions regarding particular stages of manufacturing processes less complex than the casting process, place of automation and control of parameters of the technical equipment includes most of these stages and is a homogeneous set of these parameters.

In foundry, a fact of diversification of parameters of processes and that their relation and transferring to the final quality is difficult for an unequivocal interpretation, requires a special analysis of application of significant parameter selection and ordering procedures. Application of methods of engineering ranking based on merit and/or statistics (computational intelligence) allows defining this most significant group of parameters out of all the acquired data, using them firstly for control, with the off-line method. In a further perspective, for these sub-processes (their most important parameters), possibility of use of automated activities of monitoring and control, for example by use of programmable controllers and drivers (on-line) needs to be studied.

Example described in the article show a course of an approach to implementation of the SPC method for complex processes regarding material and processing conditions, on example of foundry. Intention of the authors was to refer to certain stereotypes present at some auditors and to classic understanding of the SPC method. Some proposals were presented regarding design of a control chart. Chart of single observations turned out to be helpful in supervision of the mold pouring process on an automated line, evaluation of its stability and searching for relations between $T_{POUR}$ and occurrence of faulty castings.

A relevant feature distinguishing the SPC for the analyzed process of pouring on an automated line is recognizing exceeding of a measured parameter outside the control lines as a lack of premise to disqualify the casting as a unequivocally faulty product. It can be of concern not only considering single values, but also whole datasets. The authors have therefore proposed to use their own RSP methodology for preparation of a control chart, using the Xi example. The methodology assumes removal of the deviating values, preceded by analysis of the special causes, when probability of occurrence of the cause is high. If there are no foundations for further value removal (dataset cleaning) and a process is still unstable in the opinion of an involved employee, modification of the tolerance limits for the process can be justified. Methodology used in the algorithm of the A&DM-SPC system allows to redesign the process which was earlier stabilized, by cleaning the pilot trial. It is possible to determine the SPC parameters for the new tolerance limits.

Development of a control chart in a described way, through subsequent cleaning of the pilot trial or using the best dataset of sample assumed as a model one, will also allow for quantitative evaluation of the particular SPC parameters ($Cp$ and $Cpk$) in successive series of pours for the same assortments. This method is looked upon as a possibility to improve the stability and to arise a current competition between services maintaining the process.

Using similar rules, actions for improvement of stability of the processing parameters of the moist mold sand used for mold making on an automated line can be taken. A necessary technical condition is having an appropriate automated device for quick measurements of the mold sand properties directly after mixing, for example Vedimat.

So far, connection between evaluations of the process stability is carried out by juxtaposition with a total number of defects in a casted series of, for example, several hundred pieces. Can this be expanded? Is it possible to relate particular measured parameters (cast iron, mold sand) with the map of the defects in the series, as detailed as possible (in chronological order of their appearing on a line)? The topic is not new. One of such methods, using the marking robot, is currently being developed in a PR7 project by our coworkers in cooperation with Italian and Spanish partners. Such a full identification would allow to obtain correlation using huge datasets of measured process parameters (cast iron, mold sand) with particular types of faulty castings, with including of their detailed characteristics regarding intensity and location in the casting.

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References


