Evaluating the Statistical Process Control Data Acquisition System in a Heat Exchanger Factory

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Abstract. Manufacturers of Heating Ventilation and Air Conditioning systems in Brazil are experiencing several challenges to increase competitiveness of their operations, considering the world class companies which are continuously improving their products and processes to deliver better quality products with lower costs. To achieve this target, new opportunities for improvements in management and operation system are welcome. This paper evaluates the statistical process control data acquisition system in a company in Manaus Industrial Zone for heat exchanger manufacturing, by using BPMN for Process Mapping at current state. Following the mission of Industry 4.0, options for improvements were proposed for a new future state, considering quality improvements and resources reduction. The analysis brought process improvements, for instance increased speed of data analysis time, regarding the corrective and preventive actions taken in the production system, and its influences in reducing the failure rate of products due to leakage rate, besides the analysis of the failure rate of product performance, and the reduction of resources used to collect process data.

Keywords: SPC · Data acquisition · BPMN · Industry 4.0

1 Introduction, Context and Methodology

Brazilian industry has been facing a challenging period of high international competitiveness, including attraction of other countries with lower production costs [1]. They are also experiencing substantial changes with Industry 4.0 [2]. The world has gone through several stages of industrialization and revolutions occur with each paradigm shift. We are going through the 4th Industrial Revolution, which brings several impacts on industrial sector, starting with new business models development consumer demand increasing, and the industrial model should undergo an evolution in order to serve the new markets and quality and reliability of products improvements [3].

Additionally, unexpected events can cause more adverse scenarios in economics, like outbreak of COVID-19, which results in a recession effect, demand decrease, and

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disruption in supply chain, and a possible recovery time is impossible to predict and it will depend on many factors for economic activities restart [4], what causes new initiatives for process improvements to be pointed and evaluated.

Considering the actual scenario described above, new alternatives for quality improvements, cost reduction and production increase are requested to these companies to be more competitive. Study as [5] shows a bibliometric study of papers in last 50 years considering SPC-related themes, [6] shows an example of application of BPMN for monitoring and improving a Maintenance System and [7–9] show importance of Lean Six Sigma integration with BPMN (Business Process Model Notation).

This paper presents a case study of split Heating, Ventilation Air Conditioning (HVAC) components assembly and scenarios for improvement. It will be shown research to consider refrigeration systems and components fabrication, for promoting the company to the transformative requisites underlying the Industry 4.0 era. Then current state is described by using a BPMN map constructed. Improvement scenarios are constructed and decided which ones will be applied by using future state BPMN. Then, KPI (Key Performance Indicators) for quality and productivity are evaluated.

In this work an Action-Research (AR) methodology was used in a company of the Manaus Industrial Zone, which is one of the largest manufacturers of HVAC systems and its components in Latin America, and it has capacity to assemble indoor and outdoor units of split systems, as well as the manufacturing of heat exchangers.

AR can be used to improve Statistical Process Control (SPC) firstly recognizing the actual condition, then applying the intended practical action plan, following up the on-going actions, and then monitoring the results, and if necessary, plan a new cycle, starting by the step of recognize actual condition [10].

Manaus industrial park in Brazil has the capacity to assemble HVAC systems as well its components. The process seeks to assure quality of product and process, by monitoring key characteristics, which are measured periodically and controlled by statistical analysis. This process demands resources from the quality department and costs associated need to be controlled and, if possible, reduced.

2 State-of-Art Research

2.1 Refrigeration Systems

ASHRAE [11] defines thermal comfort as “a state of mind that expresses satisfaction with the thermal environment” [11]. Despite being a subjective concept, there are main environmental parameters that influence thermal comfort: temperature, relative humidity, thermal radiation, and average air speed, and other factors such as the clothes worn by people, the level of physical activity performed by them, among other factors [12].

Split HVAC has a part of the system located inside the environment (indoor unit), removing the heat from this environment, filtering, and circulating the air; and another part of the system is in the external area (external unit), being responsible for transferring the heat from the internal environment to the outside.

The heat exchangers are made with copper coils, through the forced passage of air from the environment through the metal fins and they are components responsible for the transfer of heat between fluids at different temperatures, using principles of heat exchange by conduction and convection [13]. And it has specific key characteristics (KC) to be controlled to assure quality of finish good, like Frames per Inch (FPI) quantity and absence of leakage under internal high pressure.

2.2 Industry 4.0 and Manufacturing Data Processing

Industry 4.0 is a concept still under development, which will apply in different ways depending on the reality of a company, but some trends will guide technological developments from now on, being the pillars of Industry 4.0, as big data analysis and monitoring, artificial intelligence, internet of things, robotics, among others [14].

Sarfraz [15] makes a differentiation between concepts of image processing (which is related to image acquisition and its digitalization, for treatment through algorithms), and computer vision (which also studies the theoretical models of the human role for application in artificial systems of data acquisition, processing, analysis and understanding of images to obtain numerical or symbolic information).

Digital image processing systems must have some fundamental steps, where the image is captured (acquisition), imperfections are removed (pre-processing), it is divided into sectors for analysis of a part of interest (segmentation), the sector of interest is analysed through algorithms, filters, artificial intelligence approaches or another method to obtain information (attribute extraction) and finally, the identification of patterns and the storage of the collected information [16].

Another important approach for analysing manufacturing data in the I4.0 is based on simulation, and in [17] is presented a mathematical model through numerical simulation for processing data about fixtures for fork-type parts manufacturing.

There are other important issues regarding manufacturing data processing in the I4.0, among which collaborative approaches, technologies and tools, namely based on the cloud, which are currently of upmost importance [18, 19].

3 Heat Exchangers and SPC Process Improvements

3.1 Process Map and Improvement Opportunities

Heat exchanger manufacturing is composed by main subprocesses below:

3.1.1 U-Bender Tube

This process receives rolls of raw material (copper tubes) and processes to specific dimensions according to product specification. Peg-Leg is defined as length difference in a "U" Shape copper tube, and it is the Critical Characteristics (KC) for this process.

3.1.2 Fin Press

Raw material (steel sheet coils) are cutted in blades and conformed with specific dimensions and shapes. Monitored KCs are the height and diameter of the holes for the tubes.

3.1.3 Package Assembly

Tubes and fins are assembled together in its specified quantities according to heat exchange model. At this point, tubes and fins are only positioned, with no permanent connection between them. There is no data collection at this stage.

3.1.4 Expander

Tube diameters is increased to give the fins and tubes a permanent set through interference fit to allow transfer of heat in final product. The controlled KCs are FPI (number of fins per inch) and tube height.

3.1.5 Brazing

The curves are mounted on the opposite side of the tubes, and then the heat exchanger goes through an automatic welding machine to connect the curves with the tubes through a brazing process. The KC controlled is the absence of fin leakage.

Business Process Model Notation (BPMN) workflow was built to map the process of data collection, as it can be seen in Fig. 1.

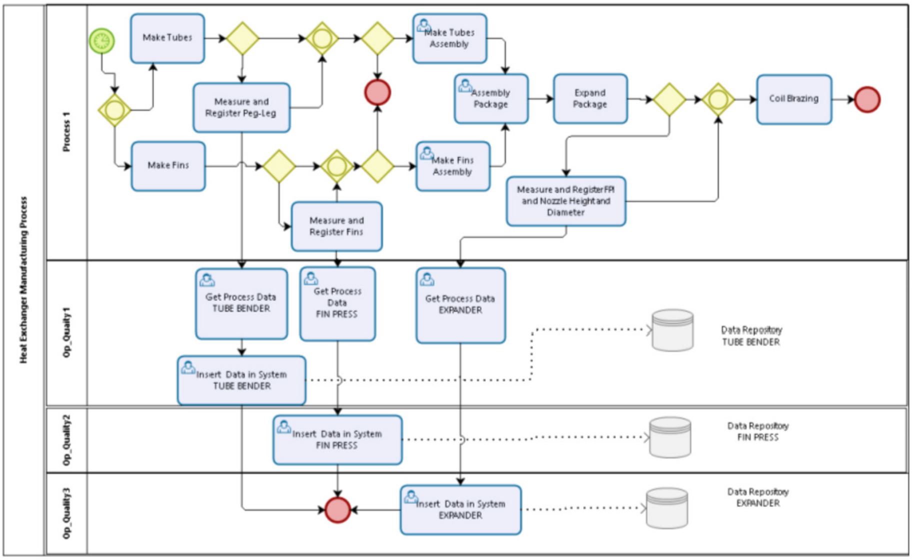


Fig. 1. BPMN of Heat Exchanger production and SPC process, considering actual state.

By analysis of BPMN As-Is, and *in-loco* check, it was possible to identify improvement opportunities, as listed below:

- Some KCs data are not reliable, are not always recorded or are recorded incorrectly.
- Manufacturing operators writes manually data on paper form.
- Quality operator needs to go to process in each machine to collect data. It takes too much time to write all read data on a sheet.

3.2 Scenario 1

Considering the amount of time required for the quality operator to go to the machines and to input data in a repository, the proposed solution to reduce both times was changing the manual control chart to an electronic form where the process operator would input information of measurement on this form.

For the application of scenario 1, electronic forms were developed. The advantages of this solution are the reduction in the processing time of the data measured registration process, the data collection and insertion process in the repository, as well as the paper consumption reduction (paperless concept). These forms were developed using the Microsoft Forms platform, as the example shown in Fig. 2.

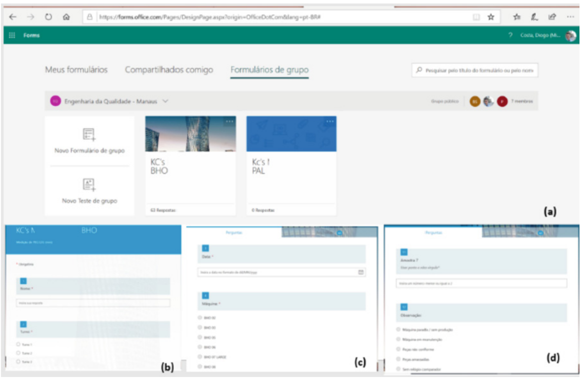


Fig. 2. Electronic form for the collection of cloakrooms and fins (a) Initial screen (b) Information of operator and shift, (c) date and machine and (d) value collected.

3.3 Scenario 2

Due to the expander process characteristics, it was not possible to apply the electronic form immediately. In addition, this process has the biggest processing time and having the most critical characteristics for product performance. An incorrect information will give us wrong conclusions and non-effective actions.

To improve these points, it was suggested to improve the measurement of KC, with the measurement of FPI and nozzles height and diameter through a system of image acquisition and processing with data storage.

Therefore, the system was designed to make the image acquisition by making a comparison with a known standard. In that way, main information is acquired from products. In the case of FPI measurement, height and nozzle diameter, the software has edge pattern detection requirements to accurately obtain the component dimensions, as shown in Fig. 3.

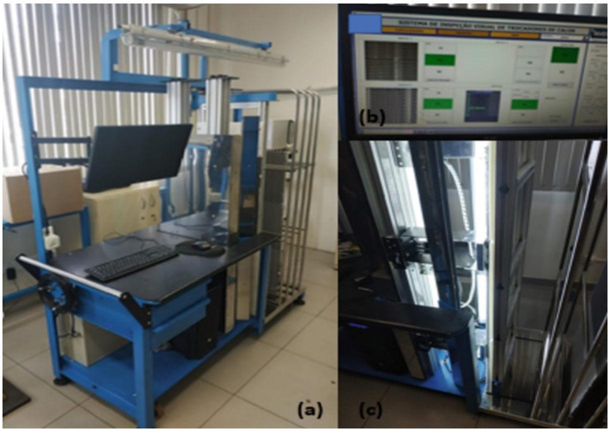


Fig. 3. System for measuring nozzles and fins (a) Initial screen (b) Information of operator and shift, (c) date and machine and (d) value collected.

In order to perform system measurement errors to be evaluated, it is necessary to quantify the variation component of the process and measurement system. So, it is necessary to proceed with a measurement system analysis (MSA), with measurement data collection and analysis through control charts. For the FPI measurement, measurement samples were collected with new system and this new system was compared with the instruments already used today, considering process variation factors. The sampling trees were made for the planning of the FPI measurements and the nozzles diameter, as shown in Fig. 4.

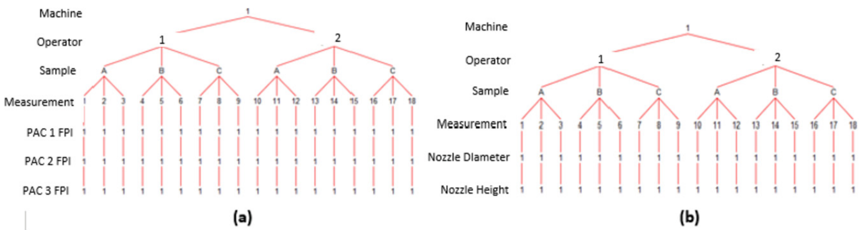
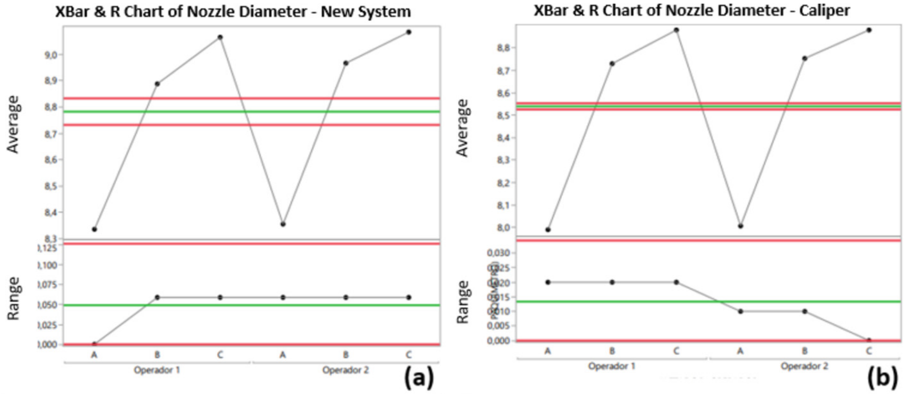


Fig. 4. Sampling trees for data collection (a) FPI (b) Height and diameter of nozzles.

Three samples of heat exchangers were selected, which were measured by 2 operators, each operator taking 3 measurements on each of the instruments. These 3 measures will be used to form subgroups, and in each of these, the mean and variation between the elements are calculated, with the objective of constructing the X-bar R charts and calculating the lower control limit (LCL) and upper control limit (UCL), as shown in Fig. 5.



Nozzle Diameter - New System Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Subgroup Size
Average	8,732131	8,782444	8,832758	Range	3
Range	0	0,049167	0,126584	Range	3

Nozzle Diameter - Caliper Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Subgroup Size
Average	8,526356	8,54	8,553644	Range	3
Range	0	0,013333	0,034328	Range	3

Fig. 5. Comparing before and after improvements (a) diameter of nozzle measured with new system (b) diameter of nozzle measured with caliper.

Range control limits is directly related to measurement error, it was possible to identify that the image inspection system presented a variation in the control limits greater than that measured with the current instrument. Besides this disadvantage, measurement error can be calculated and it is well-known, as shown in Fig. 6.

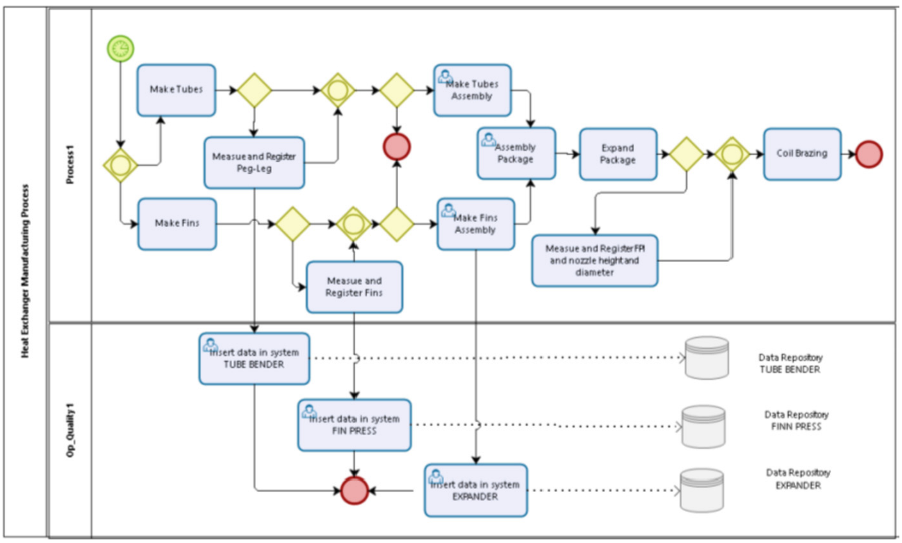


Fig. 6. BPMN of Heat Exchanger production and SPC process, considering future state and applied Scenarios 1 and 2.

In a period of 12 weeks, data were collected from the performance indicators, where weeks 27 to 31 corresponded to the process with no improvement scenarios applied, weeks 32 to 35 correspond to the application of scenario 1 and weeks 36 to 40 refer to the application of scenario 2.

Information about maintenance of related systems [13, 14] was not considered, in detail, in this paper.

4 Results

4.1 Resource Utilization

The resource utilization ratio of quality operators can be defined as the ratio between the sum of all activity times done by operator and the total available time available.

According to Table 1, each scenario application has its contribution for resource utilization decrease, and operators' necessity can be adjusted according to improvements applied in the process. A summary of each simulated scenario and resource utilization can be shown in Table 1.

In Fig. 7, it is possible to see the variation between maximum and minimum observations of occupancy rates in each week and compare with simulation result. The actual values observed from the graphs above were different from the simulated values. This can be explained due to some factors that could not be reproduced, such as variations in the standard time of the activities of operators, limitations of the simulation software that did not allow the group transfer modelling of process components, among others.

Table 1. Summary of simulated results for each scenario.

Legend	Description	Op 1	Op 2	Op 3
C0	No improvements	28%	36%	12%
C1	Electronic Forms	44%	32%	–
C2	Electronic Form and Measurement system by image	38%	–	–

4.2 Leakage Rate

Leak rate in each machine is calculated by the ratio between the quantity of products with leak issue and the quantity produced, in ppm.

After the application of scenario 1, there was a change in the leakage level of both products. However, this level change was only maintained without significant changes after the application of scenario 2, as shown in Table 2.

With the agile analysis of the data with the company main departments involved, it was possible to act in the process at the moment the anomaly occurred, the distinction when the failures are related to machine adjustment or measurement method or tool maintenance, the standardization of operations and the scheduling of preventive maintenance.

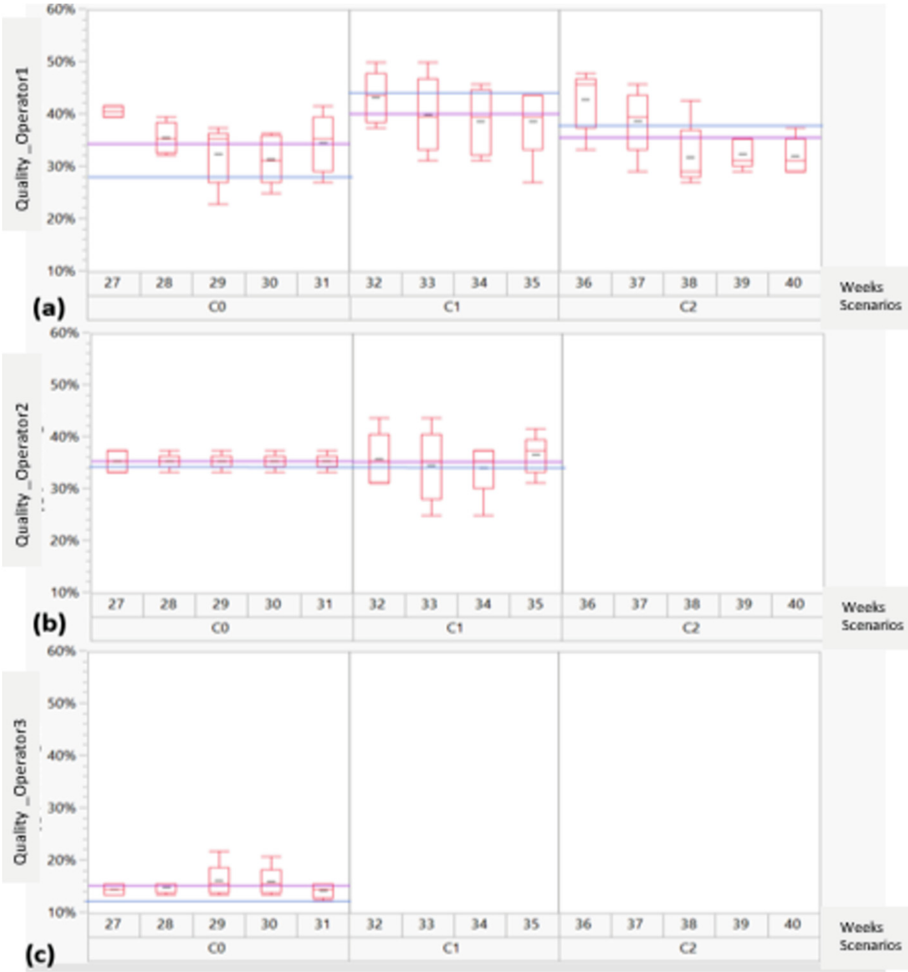


Fig. 7. Observed results of Resource Utilization for (a) Quality Operator 1 (b) Quality Operator 2 and (c) Quality Operator 3.

One of the factors that explained the reduction in the average leakage failure rate in product 2 was the adjustment of the machine and reduction of differences in length between tubes in an agile operation after trends were identified quickly.

Table 2. Leakage Rate with scenarios applied in products 1 and 2 (ppm).

Description	C0	C1	C2
Product 01	2233	962	852
Product 02	3574	1262	1430

5 Conclusions

The SPC process is very important to guarantee the quality of the process and product and achieve customer satisfaction, by sample data collection critical characteristics, its analysis of trends, failure identification and corrective and preventive actions application.

The actual state map was done with a process map that showed the critical characteristics that affects the product's quality and performance, and the indirect data collection process was mapped with the BPMN workflow.

The improvements have considered the Industry 4.0 trends, and it was decided to introduce a questionnaire for quick data collection and a component measurement system by image processing, which were implemented at two different times (scenario 1 and 2, respectively). The data collection systems proved to be very well adapted. This system showed some additional issues such as the excess of corrective maintenance at the beginning of the process operation. Even that error between measures is greater than the previous manual system, they are predictable and calculable, and the application enabled the reduction of process time.

Therefore, as the main points observed in the development of this work, it is possible to highlight:

- All the process mapping tools proved to be adequate, as it was possible to identify opportunities for improvement and to propose an action plan and a future state.
- The use of Bizagi software (which already uses BPMN notation) helped in process flow and suitability for BPM CBOK validation.
- The model was not able to reproduce all operating characteristics of the process and Bizagi software showed some limitations in accurately simulating some conditions, such as the processing of multiple products and the transfer of parts in batches, features present in other available software.
- The Measurement systems Analysis (MSA) proved to be a very effective method for validating the readings of the image system and determining the measurement error compared to other available systems
- The data collection systems based on Microsoft Forms were very well adapted, despite their original objective not to cover this type of application.
- BPMN proved to be adequate as a tool of process map. By its use, it was possible to identify opportunities for improvement and to propose an action plan and a future state.
- The image measurement system was a good resource to improve the SPC process, although there are opportunities for future studies, such as the evaluation of new measurement methods and software improvement for better integration between direct and indirect processes.

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