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Application of Statistical Process Control in Tire Manufacturing – Tread Extruder Line Case Study

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***Abstract*—The tire industry relies on precise manufacturing processes to ensure optimal performance and safety standards. Statistical Process Control (SPC) methodologies have emerged as crucial tools for enhancing quality and efficiency in tire production. This paper focuses on the implementation of SPC methodologies specifically tailored for the extrusion line in tread production - a critical stage in tire manufacturing process. It addresses practical considerations and challenges associated with implementing SPC, including implementation, data collection, analysis, and decision-making. Through this case study and real-world implementation, this paper demonstrates benefits of SPC implementation, such as defect reduction, improved product consistency, and enhanced process efficiency.**

Keywords—statistical process control, InfinityQS, process stability

I. INTRODUCTION

The tire industry plays a crucial role in ensuring safety, efficiency, and performance in various sectors such as automotive, aerospace, and transportation. With an increasing emphasis on quality assurance and cost reduction, implementing robust statistical process control (SPC) methodologies has become vital. SPC techniques enable manufacturers to monitor and control production processes effectively, thereby minimizing defects, optimizing resources, and enhancing overall product quality [1].

Statistical Process Control (SPC) stands as a foundation in modern manufacturing industries, revolutionizing how quality is ensured and maintained throughout production processes. At its core, SPC employs statistical techniques to monitor and control manufacturing processes, enabling organizations to identify variations, detect defects, and take corrective actions in real-time. By emphasizing proactive rather than reactive measures, SPC not only minimizes waste and rework but also enhances overall product quality and customer satisfaction [2].

SPC exploits variations in production process, which includes both common cause variation inherent to the process and special cause variation resulting from external factors [3]. Through the use of control charts and other statistical tools, SPC differentiates these sources of variation, allowing manufacturers to focus their efforts on address the root causes of significant deviations. Moreover, SPC facilitates continuous improvement by providing a systematic framework for data-driven decision-making, encouraging a culture of accountability and innovations within organizations.

Key to the success of SPC is the integration of quality control principles throughout the entire manufacturing process, from raw material sourcing to final product inspection. This holistic approach ensures that every aspect of the production chain is monitored and optimized for quality and consistency. Additionally, SPC encourages collaboration across departments and stakeholders, promoting a shared commitment to excellence and continual refinement [4]. As industries continue to evolve and face new challenges, the principles of SPC remain as relevant as ever, and serve as a guide for organizations that aim for high standards in quality management and process optimization.

The paper discusses specifical SPC implementation which is tailored for tread production with a triplex extrusion line in order to enhance quality management and process optimization in this part of tire industry.

In the next sections, we will explain key stages of tire manufacturing, with a specific focus on the tread extruder machine and its important role in ensuring tire quality. Section 2 will present the basics of SPC methodology. Following this, Section 3 will provide a detailed analysis of the tread extrusion process, highlighting its key parameters and challenges. Subsequently, Section 4 will outline the implementation of Statistical Process Control (SPC) through the InfinityQS Proficient software, elucidating the methodology employed for real-time monitoring and analysis. Finally, Section 5 will give the analysis of SPC reports and graphical representations, showcasing the insights gained from process data analysis, At the end benefits, conclusions and actionable recommendations for tire manufacturers based on the findings from SPC implementation will be given.

II. ABOUT SPC

SPC stands for statistical process control, which is a methodology implemented within different tools used in manufacturing and quality management that applies statistical approaches to monitor, regulate, and improve operations. It ensures that a process runs consistently and generates goods or services that match to predefined quality standards.

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When implementing SPC or any other new quality system, the manufacturing process should be inspected to identify the major waste generation locations. Waste in the production process includes everything which reduces productivity like rework of material, scrap, and additional inspection time.

The range of process variables that mass-production can handle is quite narrow. Each stage of the production process is considered under control as long as variances in the process stay within predetermined thresholds (Figure 1). Causes of undesired variations can be grouped in methods, environment circumstances, human behaviors, equipment, and raw materials [5]. Variations in mass-production can be classified into two types: usual (tolerable) and specific (unwanted). The former are random changes in process parameters that can be predicted. The SPC monitors all important process parameters throughout time to identify the root cause of specific variances. Variations that are statistically foreseeable and tolerated do not require action. However, for processes with particular sources of variation, steps must be taken in order to reduce them. These actions should be addressed and described in a production control plan [6].

SPC uses real-time graphical representation of process metrics throughout production to create a control charts. The charts and processes have two types of pre-defined limitations: control limits based on process capability (VOP – Voice of Process) and specification limits provided by the client (VOC – Voice of the Customer) [7]. Figure 2 displays the parameter distribution and related limitations [8].

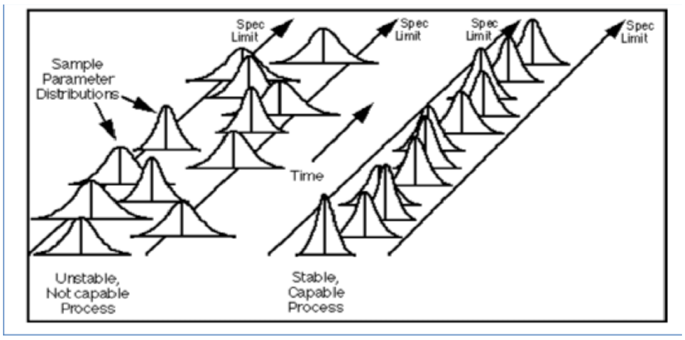


Fig. 1. Distributions of instable and stabile process

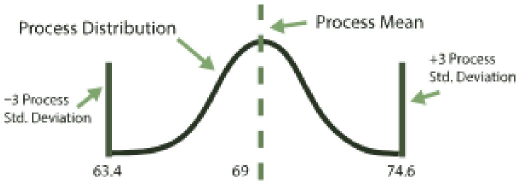


Fig. 2. Distributions in a process

Measure of a capability for a certain process is referred to as Process Capability – Cp and is given by [9]:

$$Cp = \frac{USL-LSL}{6\sigma'}. \qquad (1)$$

The USL and LSL indicate upper and lower specification limits, respectively [1], while σ' is the sigma estimator of measured process parameters which is calculated differently based on the subgroup size. Process Capability is the measure of how effectively the process satisfies the customer's requirements. Process Capability Index Cpk considers process centering and is computed using (2).

$$Cpk = \min(Cpu, Cpl) = \min\left(\frac{USL-\mu}{3\sigma'} + \frac{\mu-LSL}{3\sigma'}\right). \qquad (2)$$

Cpk is formulated as an asymmetric derivative of Cp, focusing on the specification limit closest to the process mean. Process Performance (Pp) and Process Performance Index (Ppk) can be computed analogously utilizing the same equations for Cp and Cpk where σ' is replaced with σ which is the standard deviation of measured process parameters. This difference shows up in their usage: Cp and Cpk come from sampled data, predicting future process performance. (short term), whereas Pp and Ppk come from all the data, showing how well the process performed in the past (long term). For statistically stable conditions, Cpk and Ppk show how well they match, indicating they're about the same.

III. TIRE MANUFACTURING PROCESS – TREAD EXTRUSION LINE

The tire manufacturing process typically involves several key phases, each contributing to the final product's quality, performance, and safety. This is shown in Fig. 3.

The first phase is Mixing [10]. In this phase, various raw materials such as rubber, carbon black, oils, and chemicals are mixed together in precise proportions to create the rubber compound. The compound's composition can vary, depending on the tire's intended use and desired performance characteristics (e.g., passenger, commercial, or performance vehicle tires).

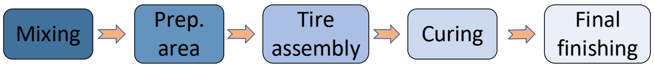


Fig. 3. Tire manufacturing phases

In the second – Prep. area phase, the compounded rubber is processed to produce different rubber components further needed for tire manufacturing. One of these components is tread product which is produced through an extruder, where it is formed into specific shape and profiles. In the next, Tire assembly phase, various components of the tire, including the tread, sidewalls, and inner liner, are assembled onto a drum or mandrel in a specific sequence. This process forms the green tire, which is the precursor to the final cured tire. Curing is a critical phase where the green tire undergoes heat and pressure treatment in a curing press. This process vulcanizes the rubber compound, bonding different components together and giving the tire its final shape, flexibility, strength, and durability. After curing, tires undergo thorough inspection and testing to ensure they meet quality and safety standards. This includes visual inspections for defects, measurements of tire symmetry and tread pattern depth, as well as testing for properties such as balance, uniformity, and traction. In this final phase any necessary finishing touches are applied to the tires, such as trimming excess rubber or adding sidewall markings. The tires are then packaged according to their specifications and prepared for distribution to customers.

The tread extrusion process in tire manufacturing is a crucial step responsible for creating the tread which is the part of the rubber in contact with the road [11]. This process begins by feeding mixed compounds into an extruder, a machine equipped with a rotating screw that transports the rubber mixture through a heated barrel. Within the extruder, the rubber is heated and pressurized, facilitating its flow through a die, which determines the shape and dimensions of the extruded tread. Depending on the process, there can be several extruders each for a different part of the tread, which are combined in the extrusion head. The head features cavities or channels that replicate the desired tread profile. Once extruded, the tread material is cooled and winded on bobbins or cut into individual sections, ready for further processing and integration into tire construction.

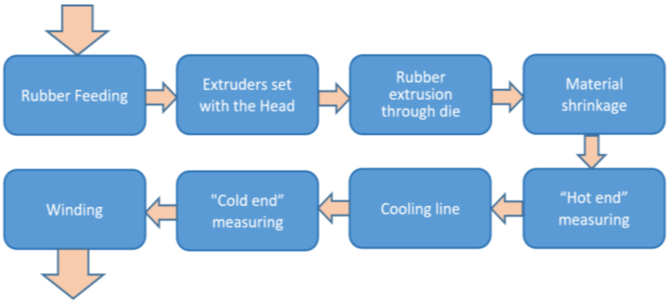


Fig. 4. Extrusion proces

The tread extrusion line in tire manufacturing encompasses a series of interconnected machines and equipment dedicated to the extrusion process. This is shown in Fig. 4. In the rubber feeding block the compound sheets of raw rubber are feed into extruders. The next block is the extruders set. Depending on the process there are extrusion line with just one extruder (simplex), two extruders (duplex), three extruders (triplex), four extruders (quadruplex) etc. Extrusion head combines conditioned rubber layers from all the extruders so the material can be pushed through the die forming adequate layer pattern and profile. Extrusion is performed through the die, and the material has to be shrunken to accommodate for rubber swelling. Measuring systems is the next block and it usually consists of weight scale, width detection system, thermal measurement system, and profile measurement system. The following, cooling line is usually implemented as a long conveying line with water cooling of the material. At the end of this line tread is again going through an on-line measuring system. Based on the measuring results non conformal tread is removed from the process while conforming material is winded on the spools or cut in pieces depending on the further tire assembly process. Tread extrusion line has to ensure consistent output in order to achieve overall quality, durability, steering characteristics and safety of the final product.

There are numerous parameters in the triplex tread extruder line which can be recorded through the SPC system (more than several hundred parameters) [12]:

- temperatures values of different extruder parts for each extruder
- speed of each extruder screw
- speed of each section of the line
- temperature and pH as well as other characteristics of the cooling water
- temperature, width, mass, different sections of profile for the extruded material (both for beginning of the line and for the end of the line)
- material loop values for each loop
- winding parameters, PID loops, tension values, cutter parameters…

For each of these both set up values and current values are recorded so the variance can be obtained in real time.

Based on these values real time SPC charts are generated - so the operator can have clear picture of the process. Also, the quality personal can have more in depth analysis and determine impact and correlation of different parameters/set of parameters on the product. This should allow for future production improvements.

IV. IMPLEMENTATION OF SPC WITH INFINITYQS

SPC implementation can be conducted using different scenarios and different set of software packages. For the case of extrusion line described here, the InfinityQS Proficient software suit was used as a SPC software package. Implementation requires several software and hardware upgrades at the production line as well as new DBMS and InfinityQS Proficient server systems. System architecture is shown in Fig. 5. Process of implementation basically consists of the following steps:

- Installation of InfinityQS Proficient services (like Proficient, DCS, and DBMS on data servers). InfinityQS Proficient consist of application services used for various purposes like defining and managing data collection, enterprise integration services, database management, alarming etc... The various information which is configured in Proficient including part numbers, machine numbers, processes, gages, test characteristics, specification limits, control limits, subgroup values, comments, process events, employee information, security levels, etc. requires DBMS system. All the data, regardless from how many projects across the whole facility they're obtained, resides in the single centralized database. Database are required to be ODBC compliant, and it can range, based on the application, from single-tier databases, such as Microsoft Access, to the high-end client-server databases, such as Oracle, Sybase, SQL Server, Informix, Progress. Proficient has its own Database Manager application which allows users to build, configure, inspect ProFicient databases, as well as add, modify, remove, import, and export entries inside them [13].
- Installing and engaging all the equipment necessary to support adequate measurement of desired process parameters This include different sensors and specific purpose devices, cards, visual communication and alarming devices, communication devices as well as connection and integration with the existing control system on the line. This part requires detailed planning and adequate level of process, engineering and technical knowledge since it is crucial for ensuring that adequate data in the adequate manner will be obtained for the SPC system.
- Adjustment the machine control system at PLCs (Programmable Logic Controller) level to enable adequate integration of new devices and additional processing of measurement and production data.
- Modification of the HMI/SCADA (Human Machine Interface / Supervisory Control and Data Acquisition) software to add new data tags, logs, visualization screens and enable collection of adequate data as well as data management and storage.
- Connecting the "on line" data storage systems with the server DBMS over the InfinityQA interface / services.

- Creating InfinityQS visual interfaces for the operators and quality personnel in order to monitor production process from different aspects.

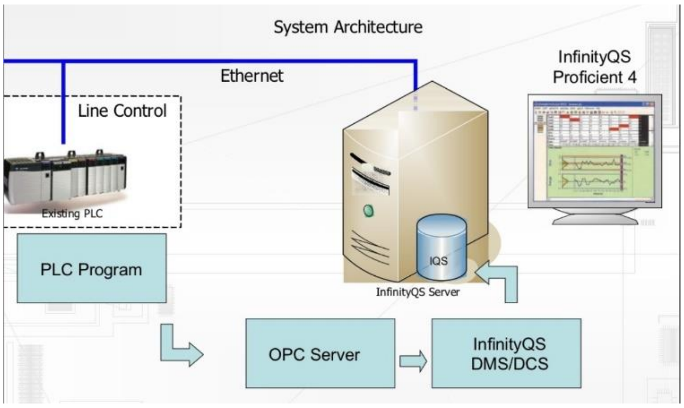


Fig. 5. Implementation of SPC – system architecture

After the implementation of the steps explained above, and initial commissioning of the system, the InfinityQS based SPC system is capable of generating control charts, graphs, reports, analysis, alarms and other process quality features. Training of users is also essential part of the implementation process.

V. INFINITYQS REPORTING, BENEFITS AND RESULTS

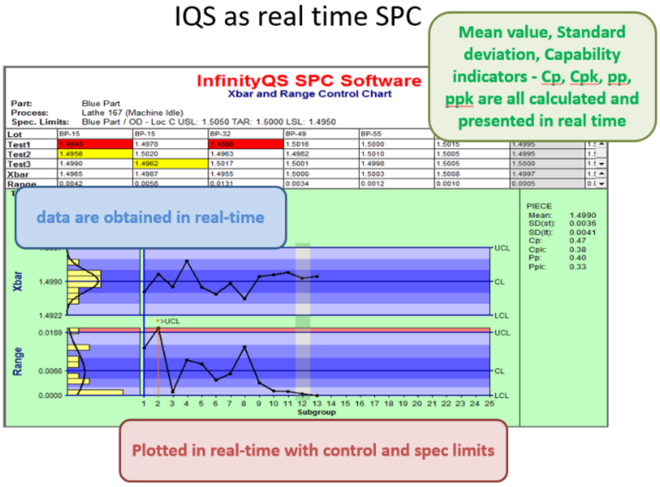
Overall benefits of SPC implementation and usage are: stabilization of the process (reduced variability), increase of process capability, reduction of scrap, improvement of the productivity, uncovering hidden process characteristics and machine abnormalities, detecting issues with raw materials, detecting other opportunities for improvement, enabling instant reaction to process changes and real-time decisions on the shop floor. This is obtained through the usage of different sets of tools while the SPC control charts are being the most utilized and most recognizable of them all.

One of most important real-time visualization charts of the process parameter that is generated by the InfinityQS is X - bar chart in combination with R chart which is displayed in Figs. 6 and 7 [14].

An X - bar chart visually depicts the mean value of a dataset across a specified timeframe, where the x-axis indicates time and the y-axis represents the average value. R chart serves as a statistical tool for monitoring data quality over time, enabling the observation of data variability and the detection of any exceptional data points in respect to the process limits and target value.

Besides these charts the Individuals and Moving Range (I-MR) Charts, P Charts, C Charts, NP Charts, Histograms, Scatter Plots, Run Charts, Pareto Charts, Box-and-Whisker Plots etc. and can be used to analyze data and understand the root cause of the unwanted process variations.

Nevertheless, real benefits of the SPC are based on the opportunity to have real time insight of the process as well as detailed analysis based on the historical data. This requires generation of corrective actions, which are either performed by operators on the line as an immediate, real time, response aimed to improve the process quality (by modifying some of the line parameters to accommodate for better Cpk, Ppk) or more planned and coordinated actions which are based on the thorough analysis of the process variations and detection of the cause of specific, unwanted variations. This systematic approach implemented with continuous improvement methodology in mind should yield more stable process in time and result in higher Cpk and Ppk of the process parameters and better conformance of the product to the desired target and limits.


IQS as real time SPC

Mean value, Standard deviation, Capability indicators - Cp, Cpk, pp, ppk are all calculated and presented in real time

InfinityQS SPC Software
Xbar and Range Control Chart

Part: Blue Part
Process: Lathe 167 (Machine Idle)
Spec. Limits: Blue Part / OD - Loc C USL: 1.5050 TAR: 1.5000 LSL: 1.4950

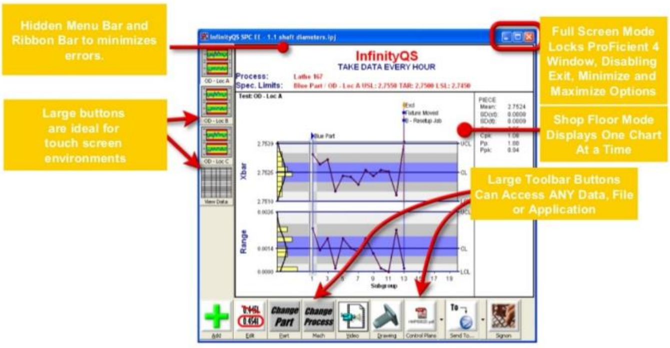
Lot	BP-15	BP-15	BP-32	BP-49	BP-55		
Test1	1.4948	1.4978	1.4886	1.5016	1.5000	1.5015	1.4995
Test2	1.4956	1.5020	1.4963	1.4982	1.5010	1.5005	1.4995
Test3	1.4990	1.4962	1.5017	1.5001	1.4998	1.5005	1.5000
Xbar	1.4965	1.4987	1.4955	1.5000	1.5003	1.5008	1.4997
Range	0.0042	0.0058	0.0131	0.0034	0.0012	0.0010	0.0005

PIECE
Mean: 1.4990
SD(st): 0.0036
SD(lt): 0.0041
Cp: 0.47
Cpk: 0.38
Pp: 0.40
Ppk: 0.33

data are obtained in real-time

Plotted in real-time with control and spec limits

Fig. 6. InfinityQS Xbar and R chart example 1


Hidden Menu Bar and Ribbon Bar to minimizes errors.

Large buttons are ideal for touch screen environments

Full Screen Mode Locks ProFicient 4 Window, Disabling Exit, Minimize and Maximize Options

Shop Floor Mode Displays One Chart At a Time

Large Toolbar Buttons Can Access ANY Data, File or Application

Fig. 7. InfinityQS Xbar and R chart example 2

Showcase of extrusion product parameter improvement of the adherence to the average and target value, after the corrective actions implementations based on the information obtained from SPC analysis is displayed in Fig, 8.

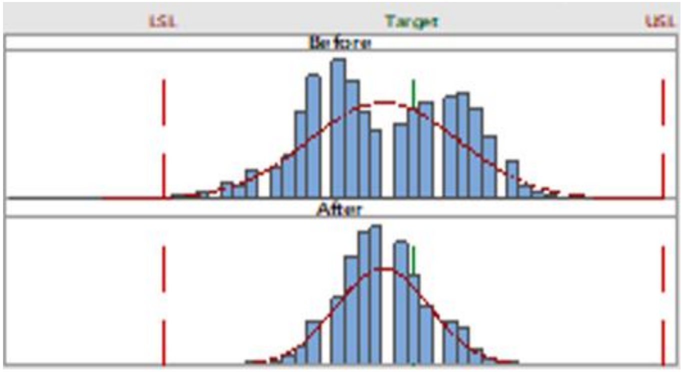


Fig. 8. Extrsuion product parameter Ppk improvement (before and after)

In the similar manner systematic, continuous improvement of Ppk after the actions implementations based on the SPC analysis are shown in Fig, 9. It can be noticed that the parameter quality which is initially out of the specification limits at the beginning is gradually improved – the Ppk value is used as a clear indicator of the conformance to the specification limits and target.

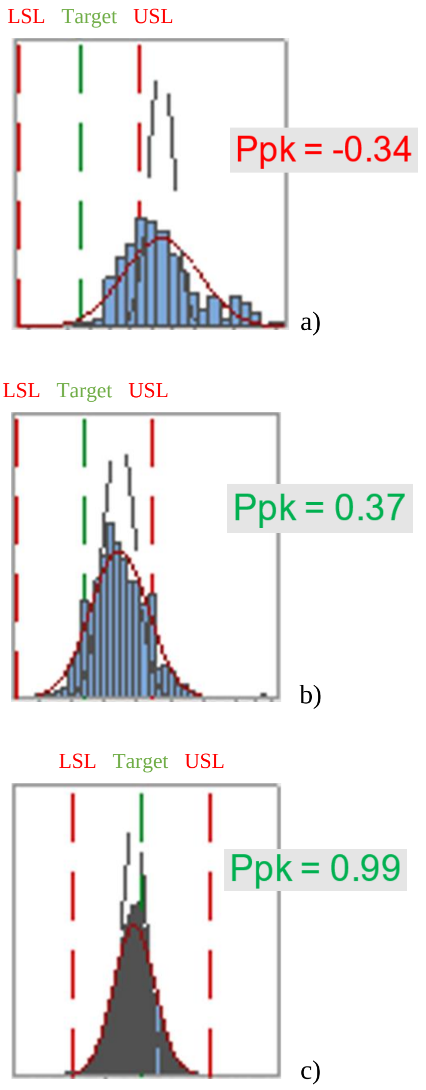


Fig. 9. Gradual extrsuion product parameter Ppk improvement: a) Baseline, b) Improvement after extruder speed modification, and c) Improvement after adjusting the line speed and PID parameters of the line loops

VI. CONCLUSION

In conclusion, it is necessary to emphasize that the implementation procedure of this project required many hours of work in different fields of electrical, computer and mechanical engineering. A systematized step-by-step approach of the implementation of Statistical Process Control (SPC) in the extrusion line required:

1. Defining project scope and system targets:
   - Identifying target manufacturing lines and processes where SPC will be implemented.
   - Clearly defining the objectives and goals of the SPC system, such as reducing defects, improving quality, or increasing efficiency.
2. Assessing additional equipment needs:
   - Evaluating the existing equipment and identify any gaps in capabilities required for SPC implementation.
   - Determining the additional equipment needed, such as sensors, data acquisition devices, or measurement instruments.
3. Acquiring Software Extensions and Licenses:
   - Selection of the SPC software that meets the specific requirements of the project.
   - Acquiring necessary licenses and extensions for the software to support the intended functionality.
4. Adjustment of PLC Program for SPC Functionalities:
   - Revision the current Programmable Logic Controller (PLC) program.
   - Modifying of the PLC program to incorporate additional functionalities required for SPC, such as data collection, monitoring, and control.
5. Modifying the OPC Server:
   - If an OPC server is used for data communication it is necessary to conduct necessary modifications to ensure compatibility with the SPC system.
   - Configuring the OPC server settings to facilitate data exchange between PLCs and SPC software.
6. Integration of the System with Local Database:
   - Determination of the structure and requirements of the local database for storing SPC data.
   - Development interfaces or protocols to enable seamless integration between the SPC system and the local database.
7. Adjust Proficient Services for Database Interaction:
   - Modifying Proficient services or middleware to enable communication with the local database.
   - Ensuring that data can be read from and written to the database as per the requirements of the SPC system.
8. System Administration Setup:
   - Defining user roles and access levels within the SPC system.
   - Implementation of security measures to protect sensitive data and ensure system integrity.
   - Setting up monitoring and maintenance procedures to keep the system running smoothly.
9. Generating Reports:
   - Designing templates and formats for SPC reports based on the project objectives and stakeholder requirements.
   - Configuring the SPC software to automatically generate reports at predefined intervals or upon request.
10. Staff Training:
    - Development of a training program for employees involved in operating, maintaining, and interpreting data from the SPC system.
    - Conduction of training sessions to ensure that staff members understand their roles and responsibilities within the SPC framework.

Only by following these steps, we were capable to systematically implement SPC and, ensure that all aspects of the process are addressed effectively.

Overall, the utilization of Statistical Process Control (SPC) in the tire manufacturing industry, namely in the Tread Extruder Line, has demonstrated significant benefits in terms of process optimization and quality assurance. This system allowed monitoring and observation of correlation and impact of numerous process parameters which are defining the functionality and behavior of the line and are the part of the recipe for the product. By analyzing this correlation, key extrusion parameters, like extrusion profile, mass, and width can be adjusted (through several iterations) by manipulating different process parameters. Manufacturers may reduce defects and increase efficiency by using SPC techniques like Cp, Cpk, Pp, and Ppk to systematically monitor and adjust production variables. This case study shows how effective SPC approaches are at finding differences in processes, cutting down on scrap, and guaranteeing that quality requirements are fulfilled. Furthermore, the integration of real-time data monitoring and analysis facilitates proactive decision-making and continuous improvement initiatives within the manufacturing environment. Moving forward, the tire industry stands to benefit significantly from the continued implementation and refinement of SPC strategies, fostering a culture of quality excellence and operational excellence. As technology advances and Industry 4.0 principles become more pervasive, SPC will remain a cornerstone in driving innovation and competitiveness across the tire manufacturing sector.

ACKNOWLEDGMENT

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