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Prevention and Early Detection of Problems Related to the Decalibration of Assembly Tools and the Loosening of Threaded Connections

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Abstract

Aim: The objective of this article was to identify and assess modern methods and tools used for monitoring the calibration status of wrenches used in assembly processes, as well as for the early detection of the degradation of bolted joints. The study sought to develop recommendations for implementing effective control procedures and technological solutions to minimise the risk of errors and enhance the quality and safety of production processes.

Methodology: The primary research methods were mathematical data analysis and participant observation.

Results: In the analysed company, wrenches are calibrated once a year in accordance with normative requirements. However, maintaining quality parameters would require the more frequent calibration of the wrenches, which would result in production line downtime. The authors proposed solutions that could extend the interval between calibrations.

Implications and recommendations: The application of various technical solutions can help maintain the required technical parameters of threaded connections without the need to halt the production line for proper wrench calibration (extending the calibration intervals).

Originality/value: The article addresses the important issue of balancing the frequency of wrench calibration with its cost and the continuity of the production process.

Keywords: torque wrenches, calibration, TQM

1. Introduction

Quality management can be defined as a set of actions, methods, techniques, and tools aimed at increasing the efficiency and flexibility of an enterprise's operations. Its main task is to satisfy the needs and expectations of customers while maintaining compliance with applicable standards (Kowalczyk, 2012).

Quality management tools and techniques enable the identification of problems, planning of corrective actions, and the evaluation of the effectiveness of implemented improvements. The use of quality methods is the foundation for effectively resolving difficulties and improving manufacturing processes. Thanks to a wide range of techniques, the right approach can be chosen for the specifics of the analysed problem. However, the greatest benefits come from combining different methods, which provides a broader perspective on the situation. As Maslow aptly noted, "a person who has only a hammer tends to see every problem as a nail" – diverse tools allow for viewing issues from multiple perspectives and developing the most optimal solutions.

Over the years the approach to quality has evolved. Initially, the concept of quality inspection was used, with its main goal being to check product compliance with customer requirements. This was followed by the development of quality control, which focused on identifying the causes of problems and providing information to production employees to improve their work. The next stage of development was the concept of quality assurance. In addition to informing production employees about irregularities, it also involved providing key information to managers, designers, and technologists. This made it possible to introduce systemic changes, such as improving a poorly designed product or correcting technological errors. Today, the dominant approach is known as management by quality, which encompasses the entire organizational structure, from top management to operational employees, and focuses on the comprehensive improvement of processes and building a quality culture (Mroczko, 2012).

Quality management in the manufacturing industry is focused on the strict control of process parameters. This approach allows to detect potential failures and non-conforming products before they occur.

In assembly processes, one of the key parameters is the quality of threaded connections such as bolts, screws, or nuts. To ensure the highest quality of bolted connections, first it is necessary to ensure the precise calibration and maintenance of the parameters of torque, pneumatic, and electric wrenches. This is an essential factor for improving the reliability and repeatability of the tightening processes, which have a direct impact on the safety and durability of the company's products.

The primary tools for supervising the maintenance of the correct tightening torque in assembly processes are Statistical Process Control (SPC) and Measurement System Analysis (MSA). MSA allows for the verification that bolts are tightened with a torque appropriate to the specification and that this torque is repeatable and reproducible within a given process. SPC helps with predicting the future behaviour of the instruments using statistical tools. By applying statistical process control in assembly processes, one can calculate after how many cycles the tightening torque will no longer be maintained at the expected level.

Despite implementing a quality management system in the enterprise and regular calibrations, significant challenges can be observed. Studies show that new devices may exhibit deviations from the set values, and over time and with the intensity of use, their precision further deteriorates (Erdem et al., 2017). Measurement accuracy is also affected by environmental factors, such as the local value of gravitational acceleration. This is an additional factor that complicates the process of ensuring measurement consistency in laboratories and production plants (Germak et al., 2018).

Quality tools including SPC and MSA do not enable full control over the behaviour of threaded connections during operation. These connections, under the influence of vibrations, can undergo relaxation, i.e. a gradual decrease in the friction force on the thread and under the bolt head, leading to self-loosening of the bolts (Włodarz, 2015), which is called bolt joint relaxation. An additional risk when using only these tools in quality management for assembly processes with bolted connections is a possible error in the torque reading by the wrench. If the company does not use additional torque control, it can lead to the mistaken belief that the equipment used is functional and capable. The lack of such verification most often manifests as an increased amount of production waste in assembly tests (e.g. leak tests), or an increased number of complaints. A noticeable increase in the number of negative test results or complaints is, however, an easy situation to detect. There are processes where, due to unstable tightening torque and the specific nature of the product, bolts tightened with a torque below or above the specification are isolated and appear randomly, which makes the problem itself difficult to detect. For this reason, it is crucial to implement effective preventive procedures and additional methods for verifying the quality of bolted connections.

This article presents several recommendations for implementing effective control procedures and technological solutions to minimise the risk of errors related to the loosening of bolts in assembly processes and unstable tightening torque, and enhance the quality and safety of production processes.

2. Literature Review

Quality management is an interdisciplinary scientific and practical field whose goal is to ensure, maintain, and improve the quality of products, services, and organizational processes. In a scientific sense, the concept has evolved from a technical understanding of quality as conformity with standards to a comprehensive approach that considers customer needs, organizational processes, and organizational culture. Quality in technical terms was originally understood as the product's conformity with specified technical requirements. Over time it has been recognised that quality also has a subjective dimension, dependent on customer expectations. In economic terms, quality is defined as "the optimal satisfaction of the user's needs" (Czapla, 2021).

Quality management (Salerno-Kochan et al., 2020) has been identified as a sub-discipline within the sciences of management and quality, which has been formally recognized in the classification of scientific fields in Poland. It covers both practical (e.g. systemic quality management, certification, auditing) and theoretical aspects (e.g. methodology of quality research, philosophical foundations of quality).

One of the key concepts in quality management is Total Quality Management (TQM). TQM involves the engagement of the entire organization in the process of quality improvement, customer orientation, a process and systemic approach, as well as continuous improvement (Czapla, 2021).

Modern quality management is based on standards such as ISO 9001 (Matuszak-Flejszman, 2021), which define the requirements for a systemic approach to quality. Specialised quality systems are also used in various sectors such as the food, automotive, and medical industries. The most important quality management tools include (Matuszak-Flejszman, 2021) the Ishikawa diagram, FMEA analysis, the PDCA cycle, the QFD method, and statistical process control (SPC). Their purpose is to identify, analyse, and eliminate sources of non-conformity and to improve production and service processes.

The high and stable quality of threaded connections is determined by a number of factors over which manufacturing companies have a direct influence through tools, e.g. calibration, validation, and preventive maintenance.

Precise calibration of assembly tools, such as torque, pneumatic, and electric wrenches, is widely recognised as one of the key elements in ensuring the high quality of assembly processes. Numerous studies emphasise that even small deviations from the defined tightening torque can significantly affect the strength and durability of threaded connections, which in turn translates into the safety and reliability of the final product (Erdem et al., 2017). Particularly in industries with high-quality requirements, including the automotive and aerospace industries, maintaining tools in a proper state of calibration is essential to minimise the risk of structural failures.

The ISO 6789-2:2017 (ISO, 2017) standard proposes a calibration frequency for torque wrenches, if the company does not use a control procedure of a period of 12 months or 5 000 cycles, whichever comes first. Depending on the operation of the production line, the specifics of the company, and the quantity of products produced, calibration may be necessary even several times a week with the very intensive use of the production line. The product itself is also important, as it should be noted that producing 1 000 units of a product containing seven screws means 7 000 cycles.

Despite the obligation of regular calibrations, practice shows that assembly tools are subject to a gradual deterioration in accuracy, due to intensive operating conditions, vibrations, temperature changes, and other environmental factors that affect the stability of the tool's parameters (Zhao et al., 2023). When calibrating wrenches one should also consider factors such as the local value of gravitational acceleration in the calibration process, which allows for greater measurement consistency between different laboratories and plants (Germak et al., 2018). Negligence in this matter can result in an uncontrolled increase in errors, which translate into quality non-conformities of the products.

Many researchers indicate that even properly calibrated and used tools do not fully protect against the problems of weakening threaded joints. The relaxation of connections, resulting from the effects of vibrations and variable loads, leads to a gradual decrease in the friction force on the thread and under the screw head, which can cause them to self-loosen. To minimise this risk, various safeguards are implemented, e.g. appropriate long and relatively thin screws, serrated washers, and adhesives, but their effectiveness is not absolute, which is why the regular inspection of the condition of the connections is necessary (Włodarz, 2015).

The development of digital technologies and Industry 4.0 opens up new possibilities for monitoring and preventing errors in assembly processes. The literature describes the implementation of tools equipped with advanced 6-axis sensors and IoT systems that collect data in the cloud and enable the use of machine learning algorithms (Bacci di Capaci & Scali, 2020) to predict the decalibration of screw tools and the degradation of connections. This allows for more precise diagnostics and planning of maintenance activities, which significantly improves the stability and quality of the assembly process.

Modern approaches to quality management place great emphasis on the continuous monitoring of tightening process parameters. In line with Industry 4.0, systems are equipped with torque sensors, and real-time data recording and analysis techniques enable the identification of deviations and immediate reaction to potential problems (Chen et al., 2018).

Effective quality management in the area of assembly using threaded connections and the use of torque, electric, and pneumatic wrenches requires the regular calibration and control of assembly tools, as well as the consideration of connection degradation and the introduction of advanced data monitoring and analysis systems. A system that takes all these factors into account is the basis for minimising the risk of delivering a product to the customer that is not properly tightened. Supervision over the proper and stable tightening torque over time helps to avoid customer dissatisfaction.

3. Goal and Methodology

The study aimed to identify and evaluate modern technical and organizational methods and solutions that enable the prevention and early detection of problems related to the decalibration of torque, pneumatic, and electric wrenches. Additionally, the authors focused on the detection and minimisation of the risk of degradation of bolted connections in assembly processes. The fulfilment of this objective included identifying the dominant factors affecting assembly quality and formulating practical recommendations to support the reliability of tools and connections under industrial conditions. The research result include recommendations for the implementation of effective control procedures and technological solutions allowing for the minimisation of the risk of errors and the improvement of the quality and safety of production processes.

The methodology was based on a multifaceted approach. A primary component was participant observation, conducted while working as a Quality Engineer in the analysed company. This position allowed direct observation of the calibration process, tool handling procedures, analysis of customer claims related to wrong torque on screws or leakages caused by too low torque, and real-time identification of process deviations. The research also involved a detailed quantitative analysis of data received from the Calibration Department, Preventive and Predictive Maintenance Department, and Manufacture Department. This data, which included tool cycle records, historical calibration results and production capacity, were processed and analysed using spreadsheet software to determine calibration requirements.

The literature review was conducted, taking into account international standards related to the calibration of torque wrenches. The recommended solutions aimed at improving the quality and safety of products in production processes that include assembly using threaded connections and torque, electric, and pneumatic wrenches, without the need to change existing processes and large financial outlays in a relatively short period, and intended as proposals for interim and effective actions.

4. Research Results

Based on the literature review, analysis of existing procedures, and observation of assembly processes in the studied company, a set of recommendations was developed to minimise the risk of assembly tool decalibration and threaded connection relaxation. The solutions cover both technical and organizational aspects. Each action is discussed separately, as depending on the company's situation it may be necessary to implement the entire set of actions in cases of a large-scale problem, or to implement them individually when there is a need for strict cost control, a low budget, and low process flexibility.

Typically, calibration processes for most operations are carried out once a year. Consequently, companies do not need to prepare their own calibration system and instead use the services of firms specialising in calibrations. In the case of the studied company, contracts for calibration services performed once a year amount to over 50 000 Euro. Due to the need for a higher frequency of calibration (see Table 1), the number of calibrations would increase from 62 to 1 187. The company opted out of obtaining a quote for an increased number of calibrations. An alternative to increasing the calibration frequency is the purchase of a mobile calibration station, which would allow for calibrations to be performed on the production line. The cost of such a station starts from 77 715 PLN.

On this basis one can assess that the purchase of a calibration station will allow for an increased frequency of calibration, while simultaneously reducing the costs incurred by the company.

Table 1. Summary of calibration quantities in assembly processes at the examined company

Line Wrench	Cycles per month	Suggested calibrations per year	Current calibrations per year
Line1 Wrench 1	88 200	212	1
Line1 Wrench 2	12 600	30	1
Line1 Wrench 3	4 410	11	1
Line1 Wrench 4	1 260	3	1
Line1 Wrench 5	25 200	60	1
Line2 Wrench 1	10 500	25	1
Line2 Wrench 2	36 750	88	1
Line2 Wrench 3	36 750	88	1
Line2 Wrench 4	630	2	1
Line2 Wrench 5	5 250	13	1
Line2 Wrench 6	15 750	38	1
Line2 Wrench 7	315	1	1
Line3 Wrench 1	2 100	5	1
Line3 Wrench 2	2 100	5	1
Line3 Wrench 3	10 815	26	1
Line3 Wrench 4	10 500	25	1
Line3 Wrench 5	2 940	7	1
Line4 Wrench 1	10 000	24	1
Line4 Wrench 2	20	1	1
Line4 Wrench 3	60	1	1
Line4 Wrench 4	160	1	1
Line4 Wrench 5	160	1	1
Line4 Wrench 6	5 000	12	1
Line4 Wrench 7	5 000	12	1
Line4 Wrench 8	5 000	12	1
Line4 Wrench 9	5 000	12	1
Line4 Wrench 10	5 000	12	1
Line5 Wrench 1	3 000	7	1
Line5 Wrench 2	6 000	14	1
Line5 Wrench 3	720	2	1
Line5 Wrench 4	1 440	3	1
Line5 Wrench 5	480	1	1
Line5 Wrench 6	120	1	1
Line5 Wrench 7	160	1	1
Line5 Wrench 8	6 000	14	1
Line5 Wrench 9	6 000	14	1
Line6 Wrench 1	1 167	3	1
Line6 Wrench 2	1 167	3	1
Line6 Wrench 3	2 333	6	1
Line6 Wrench 4	1 167	3	1
Line6 Wrench 5	1 167	3	1
Line6 Wrench 6	1 167	3	1
Line7 Wrench 1	5	1	1
Line7 Wrench 2	5	1	1
Line7 Wrench 3	5	1	1
Line7 Wrench 4	7 749	19	1
Line7 Wrench 5	34 463	83	1
Line7 Wrench 6	5	1	1
Line8 Wrench 1	1 114	3	1

Line Wrench	Cycles per month	Suggested calibrations per year	Current calibrations per year
Line8 Wrench 2	13 265	32	1
Line8 Wrench 3	1 346	3	1
Line8 Wrench 4	11 939	29	1
Line9 Wrench 1	5 040	12	1
Line9 Wrench 2	6 720	16	1
Line9 Wrench 3	33 600	81	1
Line9 Wrench 4	672	2	1
Line9 Wrench 5	1 008	2	1
Line9 Wrench 6	6 048	15	1
Line9 Wrench 7	8 064	19	1
Line9 Wrench 8	4 032	10	1
Line9 Wrench 9	5 376	13	1
Line9 Wrench 10	17 052	41	1

Source: own elaboration.

However, increasing the frequency of calibration affects the assembly process as it requires stopping the assembly line for the duration of the calibration. For the most heavily loaded station the number of calibrations was approximately 212 per year, which means that daily calibration was necessary, significantly impacting the assembly line's efficiency. In such situations the company can implement a control procedure, citing the standard's provision: "if the user does not apply a control procedure, the default interval between calibrations may be a period of 12 months or 5 000 cycles, whichever comes first. This interval begins with the first use of the torque tool" (ISO, 2017).

Another solution is to implement a tightening torque control procedure. Within the framework of Total Productive Maintenance (TPM), a mandatory check of the tightening torque should be implemented by an assembly line employee for the first piece of a production batch or once a day, whichever occurs first. This allows for the verification of whether each production batch has the correct screw tightening torques.

To verify the occurrence of threaded connection relaxation, the first step is to implement a residual torque check before shipping products for several weeks, which allows to check whether relaxation itself occurs and also estimate its significance and impact on the assembly processes. If the conclusions from the control process confirm the occurrence of problems with threaded connection relaxation, design possibilities should be analysed to change the product's design, such as using long and relatively thin screws, serrated washers, adhesive, or self-locking nuts.

For any organization, training is also important, covering tool operation, the early recognition of symptoms of decalibration and loosening connections, and checking threads for contamination. A training programme for operators focused on the quality of threaded connections would help with increasing quality awareness among operators and reduce errors among operators who are not aware of the human factor's impact on process quality.

In a situation where the implementation of the above solutions proves to be ineffective, and the problems with the quality of threaded connections persist, the company should analyse the possibility of implementing Industry 4.0 technology. The use of IoT systems, which collect data on each tightening cycle and transmit them to a database, allows for the real-time analysis of this data. Using machine learning, unusual tool operation patterns can be detected in an automated and rapid manner. Further development of the system can automatically generate service orders for the maintenance department. However, the implementation of Industry 4.0 technology requires large investment outlays, especially in companies that do not have modern infrastructure and machinery, yet it should be preceded by a detailed cost-benefit analysis.

Table 2 presents a summary of all the proposed solutions, taking into account their impact on the quality of connections, costs, and the production process. Each solution carries an implementation risk.

The lowest risk is associated with solutions that do not cause complications in the production process and are quick and cheap to implement. Monitoring residual values presents low risk as it has no impact on the manufacturing process, is quick and cheap, but requires additional resources from the company, such as quality inspectors conducting a product audit. The purchase of a mobile production station, which requires appropriately trained personnel, carries a medium risk. Design changes carry the same risk because they require additional tests and, in the case of demanding customers, may not be accepted even with positive test results. The introduction of Industry 4.0 carries a high risk due to high costs and infrastructural changes. A very high risk is associated with continuing with the current calibration method while increasing the frequency, as calibration costs will increase significantly, and additional downtime will cause a substantial drop in production line efficiency.

Table 2. Proposed solutions

Solution	Description of action	Impact on connection quality	Investment level	Impact on current costs	Impact on process efficiency	Implementation risk assessment
Increasing the frequency of tool calibration	Calibration according to the actual use of tools (according to work cycles)	Very high	Very high	Significant increase (external services)	Decrease in efficiency (line downtime)	Very high – financial and organizational risk
Purchase of a mobile calibration station	Performing on-site calibration, without the need to shut down production for a long time	Very high	Medium	Reduction of calibration costs, flexibility	Small decrease in efficiency (short stops)	Medium – easy implementation, low impact on production, requires additional, trained personnel
Implementation of a torque control procedure	Torque control by the operator for the first piece/once a day, according to TPM	High	Very low	Minimal	No impact on efficiency	Very low – simple and cheap procedure
Monitoring and control of residual torque	Periodic control of residual torque values before shipment, identification of relaxation	High	Low	Minimal	No impact on efficiency	Low – requires the involvement of additional personnel for product audits
Structural changes to connections	Use of screws with appropriate proportions, serrated washers, adhesive, self-locking nuts	Very high	Medium/High	Dependent on the intervention	No impact on efficiency	Medium – technological risk and implementation time
Training programme for operators	Training in tool operation, quality, control, recognition of error symptoms	Medium	Low	Minimal	No impact on efficiency	Very low – quick and easy implementation
Implementation of Industry 4.0 technology	IoT systems monitoring tool operation, data analysis, machine learning, automatic servicing	Very high	Very high	Initially high	Increase in efficiency, automation	High – financial and infrastructural risk

Source: own elaboration.

5. Conclusions

Ensuring the high quality of threaded connections and the early detection of problems with the decalibration of assembly tools is of practical importance in ensuring customer satisfaction and maintaining or increasing sales results. Improving the quality of products and services is closely related to the level of customer loyalty and their propensity to choose a given company again. Good quality also directly translates into increased revenues and the ability to achieve higher margins. Research indicates that problems with a product can reduce customer loyalty by 15% to 30% (Dale, 2003).

The authors analysed and presented methods for improving assembly processes. Both cheap and quick-to-implement solutions, as well as those requiring large financial outlays, were presented.

A risk assessment of the implementation of individual solutions was carried out, which showed that low-cost and organizational solutions, such as procedures, training, and monitoring, are the most effective from the perspective of quickly improving the quality of assembly processes, and they also do not generate serious threats to the efficiency and stability of production processes. Actions that require large investment, e.g. Industry 4.0 technologies, should be implemented after a thorough analysis of their profitability, depending on the company's situation.

Implementing solutions gradually, starting with quick and cheap methods and moving on to strategic investments, is the recommended strategy for improving the quality of threaded connections. Such an approach would lead to the effective minimisation of the risk of decalibration of assembly tools and the relaxation of threaded connections, while simultaneously limiting costs.

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Zapobieganie i wczesne wykrywanie problemów związanych z rozkalibrowaniem narzędzi montażowych i osłabianiem połączeń gwintowych

Streszczenie

Cel: Celem niniejszego artykułu jest identyfikacja oraz ocena nowoczesnych metod i narzędzi służących do monitorowania stanu kalibracji kluczy używanych w procesach montażowych, jak również do wczesnego wykrywania degradacji połączeń śrubowych. Artykuł dąży do opracowania rekomendacji dotyczących wdrożenia skutecznych procedur kontrolnych i rozwiązań technologicznych, które pozwolą na minimalizację ryzyka wystąpienia błędów oraz podniesienia jakości i bezpieczeństwa procesów produkcyjnych.

Metodyka: Zasadniczą metodą badawczą była metoda analizy matematycznej danych oraz obserwacja uczestnicząca.

Wyniki: W analizowanym przedsiębiorstwie klucze kalibrowane są raz w roku, zgodnie z zapisami normy. Jednak utrzymanie parametrów jakościowych wymagałoby częstszego stosowania kalibracji kluczy, co skutkowałoby przestojami linii produkcyjnej. Autorzy zaproponowali rozwiązania, które mogą przedłużyć czas pomiędzy kalibracjami.

Implikacje i rekomendacje: Zastosowanie różnorodnych rozwiązań technicznych może pozwolić na utrzymanie wymaganych parametrów technicznych połączeń gwintowanych bez konieczności wstrzymywania pracy linii produkcyjnej w celu właściwej kalibracji kluczy (wydłużenie czasu pomiędzy kalibracjami).

Oryginalność/wartość: Artykuł podejmuje ważny problem utrzymania równowagi pomiędzy częstością kalibracji kluczy a jej kosztem i ciągłością procesu produkcji.

Słowa kluczowe: klucze dynamometryczne, kalibracja, TQM