Critical electrical connections in ABB Drives factory

Elektrilised Kriitilised Ühendused ABB Drives’i tehases

MASTER THESIS

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Tallinn 2019
AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Thesis is in accordance with terms and requirements

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Chairman of theses defense commission: .................................................................

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The aim of the thesis is to map out and analyze the risks that may be associated with poor contact of critical connections. At the same time the thesis also offers a possible solution to guarantee the fastening of the joints according to the manufacturer’s specification in the first time when the connections is created. The later goal of the thesis is to compare older and newer test results and evaluate whether this solution can be implemented on assembly line.

Lõputöö eesmärgiks on kaardistada ja analüüsida riske, mis võivad kaasneda kriitiliste ühenduste halva kontakti korral. Samas pakub antud lõputöö välja ka võimaliku lahenduse, kuidas garanteerida ühenduste kinnitamise tugevus vastavalt tootja poolt ettenähtud spetsifikatsioonile esimese korraga, kohe, kui kinnitus luuakse. Lõputöö hilisem eesmärk on võrrelda värskemaid ja uuemaid katsetulemusi ning hinnata, kas antud lahendus oleks sobilik kasutada ka ettevõtte sisestel tootmisliinidel.
Thesis main objectives:

1. Map out and analyze the risks that may be associated with poor electrical connections
2. Find out the possible solution how to ensure the correct tightening torque
3. Compare old and new test results

Thesis tasks and time schedule:

<table>
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<th>Task description</th>
<th>Deadline</th>
</tr>
</thead>
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<tr>
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<td>18.2.2019</td>
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<tr>
<td>2.</td>
<td>Selection of torque tool</td>
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<td>3.</td>
<td>Analyzing risks caused by poor connection</td>
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<td>4.</td>
<td>Testing tools from assembly site</td>
<td>23.4.2019</td>
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<td>5.</td>
<td>Presenting draft version to supervisors</td>
<td>3.5.2019</td>
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</table>

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Deadline for submission of thesis: 21st of May 2019

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PREFACE

The topic of this thesis was selected by Mihkel Must, the manager of Continues Improvement and Quality team and by Kaarel Lahtvee, the leader of Manufacturing and Process Engineering team.

Working daily as Manufacturing Engineer on cabinet’s assembly line in ABB Drives factory requires to search for alternative and effective solutions to improve the product quality, a desire to reduce the time needed for product final assembly and skillful process besides support for manufacturing. It is a great opportunity to match daily work and problem solving experience with the Master’s thesis.

This thesis was completed by the supervising of TalTech University’s professor Mart Tamre and ABB Manufacturing and Process Engineering team leader Kaarel Lahtvee.
INTRODUCTION

ABB Ltd. is a multinational corporation, pioneering technology leader with a comprehensive offering for digital industries. Company operates in more than 100 countries with about 150 thousand employees. With a history of innovation spanning more than 130 years, ABB is a leader in digital industries with four customer-focused, globally leading businesses: Electrification, Industrial Automation, Motion, and Robotics & Discrete Automation. Part of Motion business is Drives and Renewables that develops, manufactures and distributes Drive units. Variable Frequency Drive units are used to run electric motors, providing electric energy with highest possible efficiency [1].

ABB Drives factory uses both calibrated pneumatic and conventional hand tools to secure electrical connections. Critical connections are always checked with calibrated hand tools. Unfortunately checking the connection is not possible sometimes due to the location of the connection inside the cabinet or the physical parameters of the tool won’t allow proper verification. Checking could be forgotten also thanks to worker’s unorganized work habit.

The objective of the Master thesis is to map out and analyze the risks that may be associated with poor contact of critical connections. At the same time the thesis also offers a possible solution to guarantee the fastening of the joints according to the company’s approved specification in the first time when the connections is created.

The later goal of the thesis is to test the current tools on assembly line. After that comparing previously acquired torque results and evaluate whether new solution can be implemented on assembly line.

Proposed solution must simplify the production process of the company since repeated inspections of critical connections consume the time and financial resources of the employer. In addition this solution makes the tool calibration process more transparent as the number of different tools in production decreases and the calibration check for the existing tools becomes longer. The focus is also on the ability to store the results to the internal database, helping to reduce the paperwork inside the company.
1. Mapping risks

1.1 Overall dangers regarding electrical connections

Industrial work is to a certain extent known for its risk for injury. However it’s still not something people often put to consideration while working in environments that risk so much injury in such a substantial way. There are numerous ways injuries can happen when doing industrial work and operating with the industrial machines. The most common cause is due to electricity [2].

Electrical hazards can cause many workplace fatalities and injuries that may result to normal workplace schedules for being disrupted. Electrocution is one of the most major cause of workplace deaths in many industries all over the world [2].

Electrical injuries may happen in various ways, such as when a worker/assembler comes into contact with an exposed electric conductor or to a part of electric circuit. This may cause heart problems, muscle spasms and loss of breath. An injury may also occur if electricity is passed from a conductor or circuit through a gas and into a grounded worker. This nature of injury is more severe and can often lead to death. In addition, workers can be burned by electrical fires or fall from heights after being shocked [2].

Poor electrical contact can cause circuit resistance to increase and impede weld current flow across the connection. Poorly made electrical connections are the joints in high or low voltage electrical devices that are not properly tightened or dirt and other contaminants come between contact surfaces [3].

Poor electrical wiring may cause problems. Because a connection runs all the way from the panel to the outlet and lighting, it’s safe to say that poor wiring is not only an annoyance, but also very dangerous. Other electrical wiring problems range from improper installation of wires to damaged or worn panels [4].

1.1.1 Loose Electrical Box Connections

Unlike the above electrical problem, loose connections in electrical boxes is a problem that’s harder to fix. Every electrical box has a device installed in it that can hinder you from taking a look
at the interior of the box to find loose connections. You can only know of a loose connection when a problem manifests itself in the system. One good example is if a light, once switched on, just flickers on and off. The problem can be pointed back to any of these three sources: a switch box, the electrical panel, or the fixture box. A loose connection will lead to heat, which causes fires.

1.1.2 Damaged Electrical Panels

An electrical panel, after several years of use, can wear out. Eventually, the primary breaker will lose grip on all fuses of the panel where the breaker makes contact. When this happens, arcing will be needed for completion of the circuit. Arcing heats up both breaker and fuses, and eventually, will burn the fuse and make the breaker lose connection with the supply line.

1.1.3 Ground Faults

Grounding an electrical circuit is very important. Without a proper ground, anything with electricity flowing through it can become dangerous. Ground faults are a good example of a stray current, which is defined as current taking on an unintended path. Hot or neutral wires that get in contact with the conductive material or the ground wire is a ground fault. Such an electrical mishap can happen in an electrical box or anywhere along the run from the panel.

Proper tightening for electrical connections can reduce the risks related to electrical dangers.

1.2 Recommendations when torquing bolts and nuts

1.2.1 Tightening Sequence

The majority of joints consist of more than one bolt and bring together surfaces that are not completely flat. The sequence of tightening bolts can have a major influence on the resulting preloads. With such joints, consideration should be given to specifying the sequence in which the bolts are to tighten. Because the joint surfaces compress, tightening one bolt in the vicinity of another will affect the preload generated by the first bolt tightened.

A good tightening sequence ensures that an even preload distribution is achieved in the joint. Since joints containing conventional gaskets have a comparatively low compressive stiffness, bolt preloads in such
joints are particularly sensitive to the tightening sequence. Based on experience, if the bolts are in a circular pattern, a crisscross tightening sequence would normally be specified. For non-circular bolt patterns, a spiral sequence starting at the middle would normally be specified [5].

1.2.2 Flange Headed Bolts

On relatively soft materials or when high tensile bolts are used, consideration should be given to the use of flange headed bolts and nuts. Such fasteners reduce the surface pressure under the nut surface reducing the amount of preload lost due to embedding. Due to the larger diameter bearing faces, generally a higher tightening torque is required because more torque is dissipated by friction [5].

1.2.3 Gaskets

Conventional gaskets are non-elastic; this results in a reduction in the bolts preload over time. The majority of such non-elastic condition usually occurs shortly after installation. This usually causes relaxation in a bolt. To reduce the effect of such problems, re-tightening of the bolts is frequently completed after allowing a period of time to elapse after initial tightening [5].

1.2.4 Embedding

Embedding is a plastic deformation that occurs in the threads of the fastener and in the joint itself. It is caused by high stresses generated by the tightening process. Such embedding results in a loss of bolt extension and hence preload. Typically, preload loss due to embedding is in the region of 10%. It increases with the number of joint surfaces being clamped and with the roughness of those surfaces. High surface pressures under the bolt head can also be a cause of excessive embedding [5].

This can be due to the use of high tensile fasteners in relatively soft materials. Hardened washers or the use of flanged fasteners can reduce such effects. Caution should be exercised in the use of short bolts clamping several interfaces together. In such joints, the small amount of bolt extension can be significantly reduced by the large amount of embedding, which can be anticipated [5].
1.3 Risks when required torque is not used

Following situations could happen when bolts and nuts are not tightened enough on critically connected connections:

1.3.1 Connections are shifting from their position during rough transport

It can be seen on Figure 1 that low torque caused the connection to come loose during transportation (by road and sea) and the components could shift from their original position.

Figure 1. Loose connection caused by low tightening torque

Reassembling the product for some reason for example difficult product’s design, doesn’t allow other components to fit in place in a first try but loosening the previously tightened connection a little bit makes the assembling much easier. Later, thanks to lack of time or negligence the connections may forgot to check. Short transportation inside production area doesn’t affect the connections to come loose and this connection may pass the quality control.
1.3.2 Weak connection causes an arcing

Here is an example of weak connection on phase bus bars and the effect of such fault. After the cabinet is commissioned and connected to power grid, a serious electrical incident can happen. On the Figure 2 the root cause of arcing is bad connection between bus bars. This type of failure can happen when worker assembles cabinet and makes the connections but bus bars are connected via bolts and nuts which are tightened by hand.

Figure 2. Burned connections on bus bars

Unequal torque on bus bar bolt connections causes increased resistance on loose connections and uneven load distribution on phases and possible effect of this failure mode is arcing. On previous picture pay attention on the gap between the rightmost bus bar connections.
Thanks to the cabinets mechanical design (Figure 3) subsequent double check is not able to see and verify if the connection is correctly made.

Figure 3. Connection is located in the back area of the final product
Product’s data logger shows the change of difference in waveworms in three phases and two modules before the safety system shut down the current flow through bus bars (Figure 4).
Closer look of damaged connection can be seen on Figure 5.

Figure 5. Damaged connection on first phase

Figures 6 and Figure 7 are showing the arcing damages on bus bars.

Figure 6. Arcing footprints on first phase bus bar  
Figure 7. Arcing footprints on third phase bus bar
On Figure 8 it is shown the appearance of bolts, washers and nuts that were removed from connections.

It is clearly seen the tightening torque was different for each bolt and nut.

Bolts from right bus bars don’t have visible damage on threads, they are shiny and sticky appearance comes from collateral damage. Tightening torque was probably below the limits. Meanwhile bolts from middle and left bus bar connections have damaged threads from over torquing that possibly happened during rushed assembly.
2. Common tightening torques used in production

2.1 Defined tightening torques for bolts and nuts

Calibrated torque tools are used in production and they are calibrated usually 2 to 4 times per year, depends on a frequency of usage. Certain automatic tightening tools, such as impact wrenches or air tools, may result a significant variations during assembly in the final torque value and the bolts preload. Different U-joints or extensions can change the final values as well. Therefore a calibrated torque tool are used for final tightening after the first connection is being made.

If correct tightening tool is achieved then assembler marks the connection with white marker and later, the person who does the double check, marks the connection with black marker (Figure 9).

Figure 9. Marking of critical connection before and after double check
Table 1 shows the tightening torque values used in production

<table>
<thead>
<tr>
<th>Combi screw/bolt</th>
<th>Elect. Connection Nm</th>
<th>Note!</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>0.5</td>
<td>Strength class 4.6 ... 8.8</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>Strength class 4.6 ... 8.8</td>
</tr>
<tr>
<td>M5</td>
<td>4</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M6</td>
<td>9</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M8</td>
<td>22</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M10</td>
<td>42</td>
<td>See exceptions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strength class 8.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hexagon bolt</th>
<th>Elect. Connection Nm</th>
<th>Note!</th>
</tr>
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<tbody>
<tr>
<td>M6</td>
<td>9</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M8</td>
<td>22</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M10</td>
<td>42</td>
<td>See exceptions</td>
</tr>
<tr>
<td>M12</td>
<td>70</td>
<td>See exceptions</td>
</tr>
<tr>
<td>M16</td>
<td>120</td>
<td>See exceptions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Torx screw</th>
<th>Elect. Connection Nm</th>
<th>Mechanical Nm</th>
<th>Note!</th>
</tr>
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<tbody>
<tr>
<td>M6</td>
<td>5</td>
<td>5</td>
<td>Frame earthling/mech.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set screw for fuses</td>
<td>Bussman Nm</td>
<td>Ferraz S. Nm</td>
<td></td>
</tr>
<tr>
<td>M8</td>
<td>20</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>M10</td>
<td>40</td>
<td>26</td>
<td>Max 5</td>
</tr>
<tr>
<td>M12</td>
<td>50</td>
<td>46</td>
<td>Max 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cable shoe</th>
<th>Elect. Connection Nm</th>
<th>Note!</th>
</tr>
</thead>
<tbody>
<tr>
<td>M8</td>
<td>15</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M10</td>
<td>32</td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M12</td>
<td>50</td>
<td>Strength class 8.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exceptions</th>
<th>Elect. Connection Nm</th>
<th>Mechanical Nm</th>
<th>Note!</th>
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<tbody>
<tr>
<td>M6 Serpress</td>
<td>5</td>
<td></td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M8 Serpress</td>
<td>15</td>
<td></td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M10 Serpress</td>
<td>35</td>
<td></td>
<td>Strength class 8.8</td>
</tr>
<tr>
<td>M10 Combi Screw</td>
<td>10</td>
<td></td>
<td>LCL-capacitor</td>
</tr>
<tr>
<td>M16 Hexagon bolt</td>
<td>80</td>
<td></td>
<td>LCL-reactor bus bar</td>
</tr>
<tr>
<td>M16 Hexagon bolt</td>
<td>70</td>
<td></td>
<td>Lifting bar</td>
</tr>
<tr>
<td>M12 Fastening</td>
<td>10</td>
<td></td>
<td>B25834-57826-K**4-1 Capacitor (Sine filter)</td>
</tr>
<tr>
<td>M10 Elec. Terminal</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M6 Fastening</td>
<td>5</td>
<td></td>
<td>SKK81/22 ja 192/22 Diode (LC Charging)</td>
</tr>
<tr>
<td>M5 Elec. Terminal</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M6 Elec. Terminal</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Needed tightening torque on bolt connections
2.2 PFMEA – Process Failure Mode and Effects Analysis

PFMEA is a step-wise means of analyzing a process, in order to identify and rate its critical failure modes and their effect. The tool is best utilized during the design phase of a project, and should be refreshed as the existing system is optimized. In production PFMEA tables are usually composed by various process-, manufacturing-, mechanical- and electrical engineers in production area to search for a solution to eliminate the risks to minimum. Once all the critical system failure modes and their associated consequences are identified and weighted, the team can arrange itself to facilitate appropriate elimination or frequency reduction of these opportunities based on the highest priority. Appropriate documentation of the potential system failures and their associated risks, facilitates the implementation of continuous improvement efforts such as engineering controls [6].

Three basic metrics are kept in mind:

Severity – Quantifying the severity of the impact of the failure effect. The scale for severity ranges from “No effect” on the low end to “Safety hazard” – up to and including “Loss of life without warning” – on the high end. Also the effect can be expressed in monetary damages, as well as destruction and delays [7].

Occurrence – Quantifying the frequency of occurrence of the failure mode. The scale for occurrence ranges from “High unlikely” on the low end to “Highly likely” on the high end. Some users, teams, and organizations will go to great lengths to provide absolute definitions for the frequency of occurrence [7].

Detection – Quantifying the ability to detect the failure at a specific process step (that is, not at a previous or subsequent step, but at the step under consideration). The scale for detection ranges from “Almost certain” on the low end to “Not possible” on the high end [7].

To evaluate how important is proper tightening torque for electrical connections between bus bars, PFMEA table (Table 2) has been created to give overview of the problems regarding critical bus bar connections and tightening. AIAG handbook was being followed when scale values were evaluated.

Scales regarding previously mentioned metrics can be found from Appendix 1 – Severity, Appendix 2 – Occurrence and Appendix 3 – Detection.
<table>
<thead>
<tr>
<th>Sub item</th>
<th>Requirements</th>
<th>Potential Failure Mode</th>
<th>Potential Effects of Failure</th>
<th>Current Process Controls - Prevention</th>
<th>Current Process Controls - Detection</th>
<th>DET</th>
<th>RPN</th>
<th>Re-commended action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical connection: Fasteners</td>
<td>Fastener - ( Nm ) M3 - 0.5...0.8 M4 - 1...2 M5 – 4 M6 - 9 M8 – 22 M10 - 42 M12 – 70 M16 - 120 LCL capacitor Exception: M10 - 10 LCL- bus bars</td>
<td>Too high torque</td>
<td>C - Loose connection due to subsequent fracture of screw. Bus bar connection overheats on the field. Arc flash. Fire inside the product.</td>
<td>9</td>
<td>1. Calibration process 2. Wrong tool used 3. Tool is broken 4. Overtightening with manual wrench</td>
<td>3</td>
<td>No check</td>
<td>10</td>
</tr>
<tr>
<td>Electrical connection: Fasteners</td>
<td>Fastener - ( Nm ) M3 - 0.5...0.8 M4 - 1...2 M5 – 4 M6 - 9 M8 – 22 M10 - 42 M12 – 70 M16 - 120 LCL capacitor Exception: M10 - 10 LCL- bus bars</td>
<td>Too low torque</td>
<td>C - Bus bar connection overheats on the field. Arc flash. Fire inside the product.</td>
<td>9</td>
<td>1. Calibration process 2. Wrong tool used 3. Tool is broken 4. Assembler inattention, forgets to tighten the connection 5. Assembler does not use pneumatic tools correctly (until ( Nm ) is reached) 6. Connection is rotating ( bolt + nut )</td>
<td>3</td>
<td>Double check with tools</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2. PFMEA table to evaluate risks that may occur regarding wrong tightening torque
Analyzing the first line from the table (dark red)

1) Electrical connection between two bus bars is tightened too much and exceeds the required spec (Table from subtopic 2.1).

Severity is graded to 9 - It means potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning. May endanger operator (machine or assembly) with warning

Occurrence is graded to 3. The frequency of the failure is very low, it may happen once during 1 - 3 year period or once per 1000000 product.

Detection is rated 10 which means that it is almost impossible to find a connection that has been overtightened. Testers or visual inspection won’t show the faulty connection during final inspection. Using torque tools with gauges don’t give the required accuracy.

Total RPN is calculated 270. Because the RPN number is quite high it is recommended to find/create and implement better solutions.

Analyzing the second line from the table (light blue)

2) Electrical connection between two bus bars is tightened too weak and the connection might be loose compared to required spec (Table from subtopic 2.1).

Severity is rated to 9 - Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning. May endanger operator (machine or assembly) with warning

Occurrence is graded 3. The frequency of the failure happening is less than rare, it may happen once during 1 - 3 year period or once per 1000000 product.

Detection got 9 points. Loose connection can be prevented by double checking the connection with calibrated tools. Production lines assemblers are double checking the critical connections every time when the cabinet is being assembled. During the connection creation and later by a person of duty.

Total RPN is calculated to 243 points. Quite high RPN number indicates that is recommended to find or create better solutions to solve issue.
3. Testing different tools

3.1 Checking torque values from commonly used assembly line tools

Four different torque tools have been picked up from assembly line and random connections have been executed with these tools. After that these torque results are compared in topic 4.

All picked tools had nominal torque value of 20 \textit{Nm}. 20 \textit{Nm} tools were chosen thanks to relatively small error compared to tools that have higher nominal torque values (i.e. 70 \textit{Nm}) according from customer experience. To get more reliable value, five bolt connections were made with each tool. The connections were reopened later with calibrated torque tool (Holex) to check the tightening torque.

More information about the calibrated tool can be found from subtopic 3.1.2.

3.1.1 Test setup

For testing the randomly selected tools from production line the following setup has been constructed as shown on Figure 10 and Figure 11.

Components that were used are close to the typical bus bar connection to simulate connections as they are in cabinet. Parts are listed in following order (assembly order):

- M10 x 35 bolt (strength class 8,8)
- M10 Washer (strength class 8,8)
- Metal plate (thickness 3 \textit{mm})
- Sheet metal plate (thickness 1,5 \textit{mm})
- Metal plate (thickness 3 \textit{mm})
- M10 washer (strength class 8,8)
- 10 spring cup washer (strength class 8,8)
- M10 nut (strength class 8,8)

Every bolt, washer and nut were used once to get more precise data result.
Figure 10. Test setup - front view – bolt, washer, metal plate, sheet metal plate

Figure 11. Test setup - back view - sheet metal plate, metal plate, washer, cup spring washer, nut
3.1.2 Tool for checking the torque

To check the previously made connections on test setup torque tool Holex has been used to check tightening torque (Figure 12). This tool is used commonly during root cause analyzes when checking critical connections by manufacturing engineers.

The tool is calibrated and has a range from 10 to 100 Nm.

Manufacturer: Holex, equipment model 655364_100.


![Holex torque wrench](image)

Figure 12. Holex torque wrench

Desired torque target is set to 20,00 ± 10 % Nm, rotation direction is counter clockwise, threshold angle 5,00 degrees and breakaway angle is 5,00. The reason why to use these parameter like counter clockwise direction or 5 degrees breakaway angle is to find out how much torque needed to open previously tightened connection (20 Nm) by 5 degrees.

Etalon wasn’t used to check if the torque values are corresponding to producer’s spec but the results can be trusted because they were executed all in same place (air temperature and humidity are constants), time and same test set.

Overall 25 connections were measured: 5 connections for each line tool (4) and demo kit. Test values are uploaded to tables on subtopics 3.1.3, 3.1.4, 3.1.5 and 0.
Uncertainty of the tool:

Result  = Measurement ± Absolute error
Absolute error  = Accuracy error + Reading error
Accuracy error  = Measurement · \(\frac{\text{Accuracy}}{100}\)
Reading error  = Units reading error · Lowest unit on display

From datasheet: Absolute error = \(±\ 1\% - k = 2\)
\[
\pm \frac{1}{100} \cdot 20 - 1 \cdot 0,01 = \pm 0,20 - 0,01
\]

Relative error
\[
E_1 [\%] = \left(\frac{\Delta x_{1-a}}{x_1}\right) \cdot 100 \% = \left(\frac{0,20}{20,00}\right) \cdot 100 = 1,00 \%
\]

Uncertainty of Holex test equipment if 20 Nm is set as nominal value
\[
x_{t0} = x_0 + \Delta x_{1-a} = 20,00 \pm 0,20 Nm
\]
3.1.3 Air compressed tools


Figure 13. Typical air tool used on assembly line

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Nominal value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nm</td>
<td>Nm</td>
</tr>
<tr>
<td>1</td>
<td>20 ± 10 %</td>
<td>17.34</td>
</tr>
<tr>
<td>2</td>
<td>20 ± 10 %</td>
<td>21.02</td>
</tr>
<tr>
<td>3</td>
<td>20 ± 10 %</td>
<td>19.41</td>
</tr>
<tr>
<td>4</td>
<td>20 ± 10 %</td>
<td>21.74</td>
</tr>
<tr>
<td>5</td>
<td>20 ± 10 %</td>
<td>18.29</td>
</tr>
</tbody>
</table>

Table 3. Test results from first air tool
When the tool accuracy was calculated after the tests were executed, the AIAG’s (Automotive Industry Action Group) handbook was used [14].

**Calculating tool accuracy**

Measurement error caused by the test device’s error

\[ u_{ST} = \frac{0.2}{2} = 0.1 \]

Measurement error caused by repeatability

\[ u_R = \frac{(Max - Min)}{2 \cdot \sqrt{3}} = \frac{(21.74 - 17.34)}{2 \cdot \sqrt{3}} = 1.2702 \]

Measurement error caused by control device’s reading error

\[ u_{RE} = \frac{1/2 \text{ Smallest digital reading}}{\sqrt{3}} = \frac{0.5 \cdot 0.01}{\sqrt{3}} \approx 0.0029 \]

Measurement error caused by metrology error

\[ u_{MET} = 0 \]

Measurement error caused by environment change

\[ u_{ENV} = 0 \]

Process variation

\[ u_A = 0 \]

Measurement variation

\[ u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0.1)^2 + (1.2702)^2 + (0.0029)^2 + 0 + 0} \approx 1.2741 \]

\[ u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 1.2741^2} = 1.2741 \]

Measurement uncertainty

\[ \Delta x_{1-\alpha} = k \cdot u = 2 \cdot 1.2741 = 2.5482 \approx 2.55 \text{ Nm} \]
Average value

\[ x_0 = \frac{\sum x_i}{n} = \frac{(17,37 + 21,02 + 19,41 + 21,74 + 18,29)}{5} = 19,56 \text{Nm} \]

Final tool accuracy

\[ x_{t,Air1} = x_0 + \Delta x_{1-n} = 19,56 \pm 2,55 \text{Nm} \]


<table>
<thead>
<tr>
<th>Test No.</th>
<th>Nominal value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nm</td>
<td>Nm</td>
</tr>
<tr>
<td>1</td>
<td>20 +/- 10 %</td>
<td>23,04</td>
</tr>
<tr>
<td>2</td>
<td>20 +/- 10 %</td>
<td>24,05</td>
</tr>
<tr>
<td>3</td>
<td>20 +/- 10 %</td>
<td>23,66</td>
</tr>
<tr>
<td>4</td>
<td>20 +/- 10 %</td>
<td>24,39</td>
</tr>
<tr>
<td>5</td>
<td>20 +/- 10 %</td>
<td>24,07</td>
</tr>
</tbody>
</table>

Table 4. Test results for second air tool
Calculating tool accuracy

Measurement error caused by the device's error

\[ u_{ST} = \frac{0.2}{2} = 0.1 \]

Measurement error caused by repeatability

\[ u_R = \frac{(Max - Min)}{2 \cdot \sqrt{3}} = \frac{(24.39 - 23.04)}{2 \cdot \sqrt{3}} = 0.3897 \]

Measurement error caused by control device’s reading error

\[ u_{RE} = \frac{1}{2} \text{ Smallest digital reading} \frac{\sqrt{3}}{2} \cdot \frac{0.5 \cdot 0.01}{\sqrt{3}} \approx 0.0029 \]

Measurement error caused by metrology error

\[ u_{MET} = 0 \]

Measurement error caused by environment change

\[ u_{ENV} = 0 \]

Process variation

\[ u_A = 0 \]

Measurement variation

\[ u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0.1)^2 + (0.3897)^2 + (0.0029)^2 + 0 + 0} \approx 0.1627 \]

\[ u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0.1627^2} = 0.1627 \]

Measurement uncertainty

\[ \Delta x_{1-a} = k \cdot u = 2 \cdot 0.1627 = 0.3254 \approx 0.33 \text{ Nm} \]

Average value

\[ x_0 = \frac{\sum x_i}{n} = \frac{(23.04 + 24.05 + 23.66 + 24.39 + 24.07)}{5} = 23.84 \text{ Nm} \]

Final tool accuracy

\[ x_{t,Air2} = x_0 + \Delta x_{1-a} = 23.84 \pm 0.33 \text{ Nm} \]
3.1.4 Regular racket head wrench

Serial number 7733; Next calibration: W11 2020

Figure 14. Typical racket head torque wrench used on assembly line

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Given value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nm</td>
<td>Nm</td>
</tr>
<tr>
<td>1</td>
<td>20 +/- 10 %</td>
<td>21.78</td>
</tr>
<tr>
<td>2</td>
<td>20 +/- 10 %</td>
<td>21.33</td>
</tr>
<tr>
<td>3</td>
<td>20 +/- 10 %</td>
<td>22.12</td>
</tr>
<tr>
<td>4</td>
<td>20 +/- 10 %</td>
<td>21.18</td>
</tr>
<tr>
<td>5</td>
<td>20 +/- 10 %</td>
<td>22.28</td>
</tr>
</tbody>
</table>

Table 5. Results from regular racket head wrench
Calculating tool accuracy

Measurement error caused by the device's error

\[ u_{ST} = \frac{0.2}{2} = 0.1 \]

Measurement error caused by repeatability

\[ u_R = \frac{(Max - Min)}{2 \cdot \sqrt{3}} = \frac{(22.28 - 21.18)}{2 \cdot \sqrt{3}} = 0.3175 \]

Measurement error caused by control device's reading error

\[ u_{RE} = \frac{1}{2} \text{ Smallest digital reading} \cdot \frac{1}{\sqrt{3}} = 0.5 \cdot 0.01 \approx 0.0029 \]

Measurement error caused by metrology error

\[ u_{MET} = 0 \]

Measurement error caused by environment change

\[ u_{ENV} = 0 \]

Process variation

\[ u_A = 0 \]

Measurement variation

\[ u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0.1)^2 + (0.3175)^2 + (0.0029)^2 + 0 + 0} \approx 0.3329 \]

\[ u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0.3329^2} = 0.3329 \]

Measurement uncertainty

\[ \Delta x_{1-a} = k \cdot u = 2 \cdot 0.3329 = 0.6659 \approx 0.67 \, Nm \]

Average value

\[ x_0 = \frac{\sum x_i}{n} = \frac{(21.78 + 21.33 + 22.12 + 21.18 + 22.28)}{5} = 21.74 \, Nm \]

Final tool accuracy

\[ x_{t \, regular} = x_0 + \Delta x_{1-a} = 21.74 \pm 0.67 \, Nm \]
3.1.5 Atlascopco Saltun SWR-30 torque wrench

Serial number 7915; Torque range 5 – 30 Nm; Next calibration: W41 2019

![Atlascopco torque wrench]

Figure 15. Atlascopco torque wrench

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Nominal value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 +/- 10 %</td>
<td>20.05</td>
</tr>
<tr>
<td>2</td>
<td>20 +/- 10 %</td>
<td>19.53</td>
</tr>
<tr>
<td>3</td>
<td>20 +/- 10 %</td>
<td>19.47</td>
</tr>
<tr>
<td>4</td>
<td>20 +/- 10 %</td>
<td>19.82</td>
</tr>
<tr>
<td>5</td>
<td>20 +/- 10 %</td>
<td>19.41</td>
</tr>
</tbody>
</table>

Table 6. Test results from Atlascopco torque wrench
Calculating tool accuracy

Measurement error caused by the device’s error

\[ u_{ST} = \frac{0.2}{2} = 0.1 \]

Measurement error caused by repeatability

\[ u_R = \frac{(Max - Min)}{2 \cdot \sqrt{3}} = \frac{(20,05 - 19,41)}{2 \cdot \sqrt{3}} = 0,1847 \]

Measurement error caused by control device’s reading error

\[ u_{RE} = \frac{1}{2} \text{ Smallest digital reading} = \frac{0.5 \cdot 0.01}{\sqrt{3}} \approx 0,0029 \]

Measurement error caused by metrology error

\[ u_{MET} = 0 \]

Measurement error caused by environment change

\[ u_{ENV} = 0 \]

Process variation

\[ u_A = 0 \]

Measurement variation

\[ u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0.1)^2 + (0.1847)^2 + (0.0029)^2 + 0 + 0} \approx 0.2101 \]

\[ u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0.2101^2} = 0.2101 \]

Measurement uncertainty

\[ \Delta x_{1-a} = k \cdot u = 2 \cdot 0.2101 = 0.4202 \approx 0.42 \text{ Nm} \]

Average value

\[ x_0 = \frac{\sum x_i}{n} = \frac{(20,05 + 19,53 + 19,47 + 19,82 + 19,41)}{5} = 19,66 \text{ Nm} \]

Final tool accuracy

\[ x_{t\text{Atlascope}} = x_0 + \Delta x_{1-a} = 19,66 \pm 0.42 \text{ Nm} \]
3.2 Possible tool selection to ensure correct tightening torque

To ensure the correct torque value to bolt connection, the calibrated and reliable torque wrench is needed. Chosen product is WrenchStar Multi Torque tool, manufactured by Crane Electronics LTD [8].

Crane Electronics Ltd. has a long term connection with other big corporations in car, ship and windmill industries where achieving correct torque to product on specific connection may be vital.

Crane Electronics Ltd. has offered an opportunity to test it in production area and evaluate the benefits if they are suitable to implement on assembly site.

3.2.1 WrenchStar Multi digital Torque tool

The WrenchStar Multi digital torque wrench is perfect for users who require torque and angle data digitally recording and a reliable, versatile and robust torque wrench [9].

The wrench has a clear OLED display screen to view the current task information, combined with a 360° light ring that is completely visible at any angle plus a vibration alert to indicate results [9].

The WrenchStar Multi works in combination with our revolutionary IQVu torque data collector or our TCI lineside controller via either an RF wireless connection or via a cable. Together, they are a perfect solution to accurately measure and tighten critical fasteners to your preset torque specifications [9].

For versatility, if the digital torque wrench goes out of range of its paired controller, it can continue to collect data with storage for up to 200 readings, allowing you to work offline. Once back in range, the WrenchStar Multi then automatically connects to the IQVu or TCI and communicates the data [9].

Features [9]:

- A 360 light ring displaying the color status of readings and vibration alert
- Can be used wirelessly (RF) or with a cable option
- Quick change battery pack for extended shift time use – Chargeable internally & externally
- Interchangeable heads with ID for auto length compensation
- A small OLED display that is clear and bright
- Capable of recording up to 200 readings offline before having to return to the data collector
- Compatible with the most advanced data collector the IQVu and our TCI lineside controller

![Torque tool heads](image)

**Figure 16. Model WS1JX-0120-C1DARX torque tool**

### 3.2.2 Torque tool heads

Crane Electronics can also offer a number of interchangeable torque wrench heads for our range of torque wrenches. These are perfect for applications that require quick, efficient and repetitive head changes for wrench operation [10].

The torque wrench heads can be supplied as standalone heads or they can be supplied with an ID chip installed. This allows the heads to communicate with our series of torque wrenches [10].

The ID chip allows the wrench to automatically adjust its torque readings, accommodating for the size and length of the particular attached head, making it quick and easy to swap between jobs and giving complete peace of mind for the customer [10].

**Features [10]:**

- Multiple sizes and head fittings
- Optimized for the IQWrench and WrenchStar Multi
- Optional ID chip available for automatic wrench recognition
3.2.3 TCI Lineside Controller

The TCI (Tool Control Interface) allows the user to connect a digital torque wrench to be used in assembly production. The WrenchStar Multi can be connected to the TCI at the push of a button [11].
The TCI allows easy management, set up and diagnostics of itself via web browsers and it can be used as a standalone and jobs can be selected and results sent to a PC or web page. The unit accepts Open Protocol commands via Ethernet to select a ‘Job’ to use with the WrenchStar Multi [11].

The TCI has a web status page that allows Ethernet properties, RF properties, logging of messages, and wrench status to be monitored. The web page mirrors the last torque and angle reading from wrench plus its torque status (LO, OK and HI). LED lights on the unit show real-time status of the wrench connection on the unit [11].

Features [11]:

- Connect a digital torque wrench at the push of a button
- Easy management, set up and diagnostics via web browsers
- Jobs can be selected and results sent to a PC or webpage
- Ethernet properties, RF properties, logging and wrench status can be monitored
- Web page mirrors last torque and angle reading from wrench plus its torque status
- LED lights show real-time status of the connection

Figure 19. TCI controller
3.2.4 User interface

Setting up a work queue is a real easy task.

Different Torque Target can be set with minimum/maximum values under one transducer (ID).

Figure 20. Setting up torque values to wrench heads
First line - After finishing the tightening, the result can be seen on display. If it’s in predefined limits it is shown as green, black color shown the connection was done manually.

Figure 21. Result (Protocol Status) is shown on PC screen
First line - If the final value is not in limits, the result is pointed out in red on screen with value.

Figure 22. Second result is presented on display screen
The same results are presented on tool with extra information. 19.18 Nm is higher than allowed torque, red LED lamp is flashing (not shown on figure 23) and the letters ‘HI’ is displayed on screen. Angle is in correct range and ‘OK’ informs user that no problems detected regarding angle.

Figure 23. Value is shown on tools display.
3.2.5 Torque values for WrenchStar Multi Torque wrench

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Nominal value</th>
<th>Actual value</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nm</td>
<td>Nm</td>
<td>Nm</td>
</tr>
<tr>
<td>1</td>
<td>20 +/- 10 %</td>
<td>19,18</td>
<td>18,83</td>
</tr>
<tr>
<td>2</td>
<td>20 +/- 10 %</td>
<td>20,59</td>
<td>20,32</td>
</tr>
<tr>
<td>3</td>
<td>20 +/- 10 %</td>
<td>20,11</td>
<td>19,47</td>
</tr>
<tr>
<td>4</td>
<td>20 +/- 10 %</td>
<td>19,91</td>
<td>19,53</td>
</tr>
<tr>
<td>5</td>
<td>20 +/- 10 %</td>
<td>21,45</td>
<td>20,72</td>
</tr>
</tbody>
</table>

Table 7. Test results from WrenchStar torque wrench

Calculating tool accuracy

Measurement error caused by the device’s error

\[ u_{ST} = \frac{0.2}{2} = 0.1 \]
Measurement error caused by repeatability

\[ u_R = \frac{(Max - Min)}{2 \cdot \sqrt{3}} = \frac{(20.72 - 18.83)}{2 \cdot \sqrt{3}} = 0.456 \]

Measurement error caused by control device’s reading error

\[ u_{RE} = \frac{1}{2 \cdot \text{Smallest digital reading}} \cdot \frac{1}{\sqrt{3}} = \frac{0.5 \cdot 0.01}{\sqrt{3}} \approx 0.0029 \]

Measurement error caused by metrology error

\[ u_{MET} = 0 \]

Measurement error caused by environment change

\[ u_{ENV} = 0 \]

Process variation

\[ u_A = \sqrt{\frac{1}{n \cdot (n - 1)} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2} = \sqrt{\frac{1}{5 \cdot (5 - 1)}} \]

\[ \sqrt{((19,18 - 20,23)^2 + (20,32 - 20,23)^2 + (19,47 - 20,23)^2 + (19,91 - 20,23)^2 + (21,45 - 20,23)^2)} \]

\[ = \sqrt{\frac{1}{20} \cdot (1.14 + 0.1169 + 0.019 + 0.1142 + 1.4445) \approx 0.3765} \]

Measurement variation

\[ u_B = \sqrt{u_T^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0.1)^2 + (0.5456)^2 + (0.0029)^2 + 0 + 0} \approx 0.3077 \]

\[ u = \sqrt{u_A^2 + u_B^2} = \sqrt{0.3765^2 + 0.3077^2} = \sqrt{0.2364} \approx 0.4862 \]

Measurement uncertainty

\[ \Delta x_{1-a} = k \cdot u = 2 \cdot 0.4862 = 0.9724 \approx 0.97 \text{ Nm} \]

Average value

\[ x_0 = \frac{\sum x_i}{n} = \frac{(18,83 + 20,32 + 19,47 + 19,53 + 20,72)}{5} = 19.77 \text{ Nm} \]

Final tool accuracy

\[ x_{WrenchMulti} = x_0 + \Delta x_{1-a} = 19.77 \pm 0.97 \text{ Nm} \]
4. Comparison of the tools

4.1 Metrics

Table 8 represents the different tools and other parameters which are needed on assembly site.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Tool accuracy</th>
<th>Relative error</th>
<th>Nominal value adjustable</th>
<th>Over/Under torque prevention</th>
<th>Assembly Speed</th>
<th>Data save</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air tool 1</td>
<td>19,56 +/- 2,55</td>
<td>13,0</td>
<td>Yes/No</td>
<td>Mechanical clutch</td>
<td>Fast/Slow</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Air tool 2</td>
<td>23,84 +/- 0,33</td>
<td>1,4</td>
<td>Yes</td>
<td>Mechanical clutch</td>
<td>Fast/Slow</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Regular torque wrench</td>
<td>21,74 +/- 0,67</td>
<td>3,1</td>
<td>Yes</td>
<td>Click when required torque is reached</td>
<td>Slow/Slow</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Atlascopco torque wrench</td>
<td>19,66 +/- 0,42</td>
<td>2,1</td>
<td>Yes</td>
<td>Click and slipping when required torque is reached</td>
<td>Slow/Slow</td>
<td>Yes/No</td>
</tr>
<tr>
<td>WrenchStar Multi torque wrench</td>
<td>19,77 +/- 0,97</td>
<td>4,9</td>
<td>Yes</td>
<td>Flashing lights on tool/PC display when required torque is reached</td>
<td>Slow/Slow</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

Table 8. Comparing different parameters of tool

MultiStar wrench has quite high relative error compared to other torque tools. It comes from a method how the tool accuracy was calculated for the tool – if other tools had presumable nominal value 20 Nm, MultiStar had different final value for every measurement. Exactly 20 Nm with every connection couldn’t
be executed. Process variation was included when calculating total measurement uncertainty that raised the variation and the final accuracy seems less accurate.

Benefits are data result saving, easily adjustable nominal values and warning signs to user if final value has exceeded the limits.

### 4.1.1 Cost of tools

Table 9 presents the costs of each tool and their additional equipment *.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Price</th>
<th>Required Quantity</th>
<th>Additional equipment price **</th>
<th>Required Quantity</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlascopco Air tool</td>
<td>EUR</td>
<td>Pc</td>
<td>EUR</td>
<td>Pc</td>
<td>EUR</td>
</tr>
<tr>
<td></td>
<td>3669.68</td>
<td>1</td>
<td>32.62</td>
<td>1</td>
<td>3724.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>21.75</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Regular racket head torque</td>
<td>EUR</td>
<td>Pc</td>
<td>-</td>
<td>-</td>
<td>EUR</td>
</tr>
<tr>
<td>wrench</td>
<td>231.05</td>
<td>1</td>
<td></td>
<td></td>
<td>231.05</td>
</tr>
<tr>
<td>Atlascopco racket head torque wrench</td>
<td>EUR</td>
<td>1</td>
<td>21.75</td>
<td>1</td>
<td>497.45</td>
</tr>
<tr>
<td>WrenchStar Multi Torque tool</td>
<td>EUR</td>
<td>1</td>
<td>1718.06</td>
<td>1</td>
<td>5478.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>152.22</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

* The prices of the tools listed in the table are presented on relative scale, not on an absolute scale.
** Tool needs additional parts like heads, TCI or extensions that has to survive impact etc. for proper functioning

Wrenchstar torque tool is more expensive compared to other tools. Additional parts needed for proper function will rise the costs even higher. Common Air tools are also expensive. Regular wrenches that won’t need extra equipment at all are the cheapest.

### 4.1.2 Monetary expense for company

Possible saving/expense when replacing current tool set (Figure 25) with Wrenchstar Torque tool in production.

\[
\text{Cost}_{\text{Now}} = 7 \cdot \text{Regular torque wrench} + 3 \cdot \text{Atlascope torque wrench (with extra equipment)} \\
= 7 \cdot 231,05 + 3 \cdot (475,70 + 21,75) = 3174,95 \text{ €}
\]

\[
\text{Cost}_{\text{MultiWrench}} = \text{Torque tool} + \text{TCI} + 3 \cdot \text{Heads} = 3608,68 + 1718,06 + 3 \cdot 152,22 = 5783,40 \text{ €}
\]

\[
\text{Expenses} = \text{Cost}_{\text{MultiWrench}} - \text{Cost}_{\text{reg}} = 5783,40 - 3174,95 = 2608,45 \text{ €}
\]

![Figure 25. Current tool set what is planned to be replaced](image)
After calculations it can be seen that replacing 10 tools (and their additional equipment) with one MultiStar torque wrench, the expenses for company is approximately 2,6 K€ higher than they are now.

Please note that indirect expenses (i.e. calibration process, quality upgrade, database creation, trainings to use, cost for utilities etc.) weren’t considered in calculations.

4.1.3 Indirect saving

Following there isn’t possible to calculate how much company can win because data is confidential. Indirect evaluation shows that company can benefit from implementing the MultiStar Wrench on assembly site. Some fields can be pointed out:

- Time from double checking (approximately 40 h per week) – extra person who does the double checking is not needed and this person could be arranged to production
- Quality – Failures regarding weak connections on test field are taken to minimum
- TCI controller for different wrenches – depends how many tools will be replaced but TCI won’t be needed for every torque tool
- Calibration (Quality) – Calibration period is defined and informs user if it has passed.
- Calibration (Quality) – Some research can be done on tools working spec regarding calibration. If the system detects the calibration value set point has been shifted it has to warn user to send it to person who does the preventive calibration for tool.
- Cost of new tools – expenses to different tools can be reduced if torque wrench can cover most of the torque range that is used on assembly line
- Saving from R&D – easily adjustable torque wrench can save some expenses from additional tools that are used for R&D stage products
- Assembly time – worker doesn’t have to search for different torque tools when it can be done using one (must have predefined tightening sequence) tool
- Assembly time – marking with different colors on connections not needed any more
- Traceability – values for the tightened connections can be taken out from database after years of service.
4.2 Pros & Cons of WrenchStar Multi Torque tool

4.2.1 Pros

- Results are saved to tool’s (internal) database – up to 200 results
- Results will be saved to local database via RF
- Mobility to use in different areas of the factory
- Accurate results compared to previous tools used on assembly line
- Wide working range – from 10 to 120 Nm
- Easy to adjust if torque specs changes are needed
- Ergonomical – lightweight and small by dimensions
- Calibration once a year
- Warning to user if the connection got over/under torque - Upper and lower limits tells user with lights and vibration when the correct value range has been reached

4.2.2 Cons

- Expensive tool and equipment compared to other torque wrenches
- Battery – spare battery needed if intensive use
- Training for persons who want to use it
- Removable heads can be used one cycle during work queue
- Extensions may still be needed if product design won’t allow easier assembly
- Air tools still needed to reach faster assembly
5. **Implementing torque tool to assembly line**

Before releasing the tool on assembly line following steps have to be overviewed:

1. **SQL database modifications**

   Contacting IT support and give an input to create extra table where can data be saved from tool.

2. **Ordering the tool to factory and let it use on a small area of production for some period**

   Training of highly skilled workers is needed and later the tool can be used on assembly site. Any recommendation and feedback in the beginning of implementation from regular users simplifies the implementation process.

3. **Checking tools working sequence**

   Tool’s work sequence has to be overviewed. Must get better understanding how the calibration stays test of time. Also have to find out is it possible to write an alarming message to tool’s sequence if calibration set point is has been shifted after some period of use.

   Frequent cooperation and communication with tool manufacturer sales representatives is needed.

4. **Comparing the results**

   During implementation period connections done by MultiStar Wrench need to be recheck (and SQL values). It can confirm that the tool is suitable to use in a whole factory, or even in Local Business Unit.
5.1 Process flow

Product order is released to production and product’s technical data is checked by (senior) assembler or manufacturing engineer. If the cabinet is standard product (critical connection quantity and locations have been previously defined), assembler have to use Multistar wrench to tighten the connections and results will be saved to database (SQL). Other connections are done by regular tools. If cabinet is ready, it will be checked visually by Final control worker and functional testing can be started. If the system detects an error during test (for example torque value data is missing or exceeds the limits on some critical connections) the test will fail and cabinet is sent back to assembly line.

After the engineer has made the corrections to SQL, the connections have to be retightened with MultiStar wrench and cabinet can sent back to Final control. If no errors detected during test and it passes with positive then the cabinet is ready and production order can be closed.

If connections are not defined (unstandardized product) the manufacturing engineer modifies database or informs IT support to write correct parameters to SQL. After that the same process can continue as previously described.

Following figure on next page presents a work flow visually when the new tool will be implemented on assembly line and how it’s going to be used in a future for every day purposes in factory.
Typical cabinet assembly process map
Manufacturing Engineering
Production Planner
Final Control
Assembler

1. Released order
   - Checking cabinets layout, assembly drawings etc.
   - Checking how many critical connections are included in cabinet
   - Standard product
   - No
   - Yes

2. Inform assembly worker
   - Checking IT support to modify SQL database

3. Start / Continue with the assembly
   - Using WrenchStar Multi torque tool to tighten the critical connections
   - Issues detected?
     - Yes
     - No
   - Torque and position values to SQL

4. Finishing cabinet
   - Major rework needed?
     - Yes
     - No
   - Continue with the assembly
   - Use regular torque wrench

5. Opening a critical connection?
   - Yes
   - No
   - Informed Manufacturing Engineer

6. Test passes?
   - Yes
   - No
   - Uncomplete torque and position values in SQL
   - Delete necessary values from SQL
   - Informed assembly worker

7. Yes
   - Finished order
   - No
6. Summary

In conclusion bad connections between electrical contacts may cause component shifting inside the device during transportation. In more severe cases short circuit, arching, fire or even explosion if the device is connected to power grid. Bad connections can be eliminated by correct tightening torque on bolt connections that is defined by manufacturer.

After creation and analyzing of PFMEA table regarding torque specs, it showed that the risk priority numbers are high. No matter if the connection is too weak or too tight. Even though the occurrence may be relatively small and these incidents may occur once in a 3 year period, the risk in safety and financial impact is not acceptable. Complex design of the product or worker careless will increase the risk of products failure. Additional actions like using smart tools in addition to double checking by different persons and marking the connections must be taken to ensure that tightening torque for the specific connection is in its limits.

Random tests with commonly used torque tools showed the variance of tightening torque that is applied to connections. Some calibrated tools had set point close to the working limits while the deviation was small, other tools had set point according to calibration data but the deviation was high. One possible solution how to secure connections in the first attempt is to use digital Torque Wrench. It helps to reduce waste caused by double checking and quantity of assembly tools. Tool has to notify the worker if the connection has done correctly and save the torque value to the local database (saving values to database helps to improve tracing of the product). If the torque value is not in its specified limits, the tool has to warn user to redo the connection until correct torque value has been reached.

From comparison between different tools the digital torque tool was selected – the MultiStar Torque Wrench. The benefits are that tool has programmable and adjustable working range and mobility. These functions are a big benefit for larger production site because one tool can replace several others and the smart tool is working range is not limited by the cable length, making the production more agile. User interface is easily understandable and gives the worker necessary information about the joint quality. Joint data is saved to tools data logger and is received by tool controller and saved to local data base.

Although the tool and its additional parts are expensive compared to regular tools used in the production, the benefits can have a cost saving in the long run. Further experiments and time studies have to be conducted to see if this tool helps reducing wasted time caused by delays in production. One major saving
can come from eliminating double checking of connections, but also time spent on rework and possible field failures.
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   (18.2.2019)


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   (27.5.2019)
## APPENDIX

### Appendix 1 – Severity

<table>
<thead>
<tr>
<th>Effect</th>
<th>Criteria: Severity of effect on Product (Customer Effect)</th>
<th>Rank</th>
<th>Effect</th>
<th>Criteria: Severity of effect on Product (Customer Effect)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure to Meet Safety and/or Regulatory Requirements</strong></td>
<td>Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.</td>
<td>10</td>
<td><strong>Failure to Meet Safety and/or Regulatory Requirements</strong></td>
<td>May endanger operator (machine or assembly) without warning</td>
</tr>
<tr>
<td></td>
<td>Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.</td>
<td>9</td>
<td></td>
<td>May endanger operator (machine or assembly) with warning</td>
</tr>
<tr>
<td><strong>Loss or Degradation of Primary Function</strong></td>
<td>Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).</td>
<td>8</td>
<td><strong>Major Disruption</strong></td>
<td>100% of product may have to be scrapped. Line shutdown or stop ship.</td>
</tr>
<tr>
<td></td>
<td>Degradation of primary function (vehicle operable, but at reduced level of performance).</td>
<td>7</td>
<td><strong>Significant Disruption</strong></td>
<td>A portion of the production run may have to be scrapped. Deviation from primary process including decreased line speed or added manpower.</td>
</tr>
<tr>
<td><strong>Loss or Degradation of Secondary Function</strong></td>
<td>Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable)</td>
<td>6</td>
<td><strong>Moderate Disruption</strong></td>
<td>100% of production run may have to be reworked off line and accepted.</td>
</tr>
<tr>
<td></td>
<td>Degradation of secondary function (vehicle operable, but comfort/convenience functions inoperable).</td>
<td>5</td>
<td></td>
<td>A portion of the production run may have to be reworked off line and accepted.</td>
</tr>
<tr>
<td><strong>Annoyance</strong></td>
<td>Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (&gt;70%).</td>
<td>4</td>
<td><strong>Moderate Disruption</strong></td>
<td>100% of production run may have to be reworked in-station before it is processed.</td>
</tr>
</tbody>
</table>
Appearance or Audible Noise, vehicle operable, item does not conform and noticed by many customers (50%).

A portion of the production run may have to be reworked in-station before it is processed.

Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%).

Minor Disruption

Slight inconvenience to process, operation, or operator.

No effect

No discernible effect.

* Table is taken from company’s internal database, reference can’t be done

Appendix 2 – Occurrence

<table>
<thead>
<tr>
<th>OCCURANCE</th>
<th>Criteria: Occurrence of cause - PFMEA (Incidents per items/vehicles/opportunities)</th>
<th>Failure rate</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very High</td>
<td>&gt;= 100 per thousand &gt;= 1 in 10</td>
<td>Every day</td>
<td>10</td>
</tr>
<tr>
<td>High: repeated failures</td>
<td>50 per thousand 1 in 20</td>
<td>Once per 2-3 days</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>20 per thousand 1 in 50</td>
<td>Once in a week</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>10 per thousand 1 in 100</td>
<td>Once in a month</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Occurrence</td>
<td>Control Schedule</td>
<td>Scale</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------------------------</td>
<td>--------------------------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>Moderate: occasional failure</strong></td>
<td>2 per thousand 1 in 500</td>
<td>Once in 3 months</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0.5 per thousand 1 in 2000</td>
<td>Once in 6 months</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.1 per thousand 1 in 10000</td>
<td>Once in a year</td>
<td>4</td>
</tr>
<tr>
<td><strong>Low: relatively few failures</strong></td>
<td>0.01 per thousand 1 in 100000</td>
<td>Once in 1-3 years</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>&lt;= 0.001 per thousand 1 in 1000000</td>
<td>Once in 3-5 years</td>
<td>2</td>
</tr>
<tr>
<td><strong>Remote: failure is unlikely</strong></td>
<td>Failure is eliminated through preventive control</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

*Table 11. Occurrence scale*

*Table is taken from company’s internal database, reference can’t be done.*
## Appendix 3 – Detection

<table>
<thead>
<tr>
<th>Opportunity for detection</th>
<th>Criteria: Like hood of Detection by Process Control</th>
<th>Inspection</th>
<th>Likelihood of Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>No detection opportunity</td>
<td>Absolute of certainty of non-detection: 1. No current process control; 2. Cannot detect or is not checked</td>
<td>10</td>
<td>Almost Impossible</td>
</tr>
<tr>
<td>Not likely to detect at any stage</td>
<td>Controls will probably not detect: 1. Control is achieved with indirect or random checks only 2. Failure mode/or Error (Cause) is not easily detected (e.g., random audits)</td>
<td>9</td>
<td>Very remote</td>
</tr>
<tr>
<td>Problem Detection Post Processing</td>
<td>Controls will probably not detect: 1. Control is achieved with visual inspection only 2. Failure Mode detection post-processing by operator through visual/tactile/audible means</td>
<td>8</td>
<td>Remote</td>
</tr>
<tr>
<td>Problem Detection at Source</td>
<td>Controls have poor chance of detection: 1. Control is achieved with double visual inspection only 2. Failure mode detection in-station by operator through visual/tactile/audible means or post-processing through use of attribute gauging (go/no-go, manual torque check (clicker wrench, etc.)</td>
<td>7</td>
<td>Very Low</td>
</tr>
<tr>
<td>Problem Detection Post Processing</td>
<td>Controls may detect: 1. Control is achieved with charting methods, such as SPC 2. Failure Mode detection post-processing by operator through use of variable gauging or in-station by operator through use of attribute gauging (go/no-go, manual torque check/clicker wrench, etc.)</td>
<td>6</td>
<td>Low</td>
</tr>
<tr>
<td>Problem Detection at Source</td>
<td>Controls may detect: 1. Control is based on variable gauging after parts have left the station 2. Failure Mode or Error (Cause) detection in-station by operator through use of variable gauging or by automated control in-station that will detect discrepant part and notify operator (light, buzzer, etc.). Gauging performed on setup and first-place check (for set-up causes only)</td>
<td>5</td>
<td>Moderate</td>
</tr>
<tr>
<td>Problem Detection Post Processing</td>
<td>Controls have a good change to detect 1. Error detection is subsequent operations 2. Failure Mode detection post-processing by automated controls that will detect discrepant part and lock part to prevent further processing.</td>
<td>4</td>
<td>Moderately High</td>
</tr>
</tbody>
</table>
| Problem Detection at Source | Controls have a good change to detect:  
1. Error detection in-station, or error detection is subsequent operation by multiple layers of acceptance. Cannot accept discrepant part.  
2. Failure Mode detection in-station by automated controls that will detect discrepant part and automatically lock part in station to prevent further processing | 3 | High |
|-----------------------------|--------------------------------------------------------------------------------------------------|---|---|
| Error Detection and/or Problem Prevention | Controls almost certain to detect:  
1. Error detection in-station (automatic gauging with automatic stop feature) Cannot pass discrepant part.  
2. Error (Cause) detection in-station by automated controls that will detect error and prevent discrepant part from being made | 2 | Very High |
| Detection not applicable; Error Prevention | Controls certain to detect:  
1. Discrepant parts cannot be made because item has been error-proofed by process/product design  
2. Error (Cause) prevention as a result of fixture design, machine design or part design. | 1 | Almost Certain |

<table>
<thead>
<tr>
<th>Inspection types:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Error-proofed (in-line 100% inspections)</td>
</tr>
<tr>
<td>B</td>
<td>Testers</td>
</tr>
<tr>
<td></td>
<td>Manual Inspection (visual testing, common testing methods)</td>
</tr>
</tbody>
</table>

Table 12. Detection scale

* Table is taken from company’s internal database, reference can’t be done.
Appendix 4 – Torque wrench and TCI datasheets

The WrenchStar Multi - Production Wrench

- The WrenchStar Multi Digital Torque Wrench is for customers who require Torque and Angle Data digitally recording.
- Includes a 360° light ring so you can view the status of readings and Jobs regardless of how you hold the Wrench.
- An accurate angle gyro.
- RF – Can be used wirelessly (RF) or with a cable option.
- Quick change battery pack for extended shift time use – chargeable internally & externally.
- Interchangeable Heads with ID for automatic length compensation.
- Incorporates a small OLED display that is clear and bright.
- Vibration alert.
- The means to record up to 200 readings offline before having to return to the Data Collector.
- Compatible with the most advanced Data Collector the IQVu and also the TCI Lineside controller.

Crane Electronics Ltd
Watling Drive
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Hinckley LE10 3FY
Tel: +44(0) 1455 25 14 88
www.crane-electronics.com

Crane Electronics Inc
1260 11th Street West
Milan, Illinois 61264
USA
Tel: +1 309-787-1263
www.crane-electronics.com
The Wrenchstar Multi technical specifications:

- Operating temp range: -20 to +50°C.
- Storage temp range: -20 to +50°C.
- Humidity: 10-75% non-condensing.
- IP Rating: IP40 (Indoor use only).
- Reading storage: 200 readings.
- Sampled: Every 20 micro seconds (50,000) per second.
- Zero Stability: <0.1% FSD/°C.
- Static Accuracy: ±0.25% FSD.
- Angle Measurement: Sample every 1000 micro seconds.
- Frequency Response: 75Hz to 4500Hz.
- Battery: Rechargeable 3.7v Lithium Ion.
- Capacity: 2600mAh.
- Communication with IQVu plus: 2.4GHz RF & Cable.
- Communication with TCI: 2.4GHz RF with Open Protocol or Crane Protocol.

<table>
<thead>
<tr>
<th>Sales Code</th>
<th>Range</th>
<th>Insert</th>
<th>Weight (gr)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSL10-00/06-C1DAARX</td>
<td>10Nm DIN Insert</td>
<td>9X12 mm</td>
<td>933</td>
<td>380</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>10Nm Fixed Head</td>
<td>933</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>25Nm DIN Insert</td>
<td>9X12 mm</td>
<td>933</td>
<td>380</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>25Nm Fixed Head</td>
<td>933</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>75Nm DIN Insert</td>
<td>9X12 mm</td>
<td>933</td>
<td>380</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>75Nm Fixed Head</td>
<td>933</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>120Nm DIN Insert</td>
<td>9X12 mm</td>
<td>933</td>
<td>380</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>120Nm Fixed Head</td>
<td>933</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>180Nm DIN Insert</td>
<td>14x18 mm</td>
<td>1474</td>
<td>613</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>180Nm Fixed Head</td>
<td>14x18 mm</td>
<td>1474</td>
<td>613</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>250Nm DIN Insert</td>
<td>34x46 mm</td>
<td>1925</td>
<td>788</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>250Nm Fixed Head</td>
<td>34x46 mm</td>
<td>1925</td>
<td>788</td>
</tr>
<tr>
<td>WSL10-00/05-C1DAARX</td>
<td>300Nm Fixed Head</td>
<td>34x46 mm</td>
<td>1925</td>
<td>788</td>
</tr>
</tbody>
</table>

Interchangeable ID Heads also available

For more information or for a quote, call +44 (0) 1455 25 14 88 or email sales@crane-electronics.com.

Crane, the force in torque management

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The Wrenchstar Multi data sheet [12]
The TCI - Lineside Controller

- Allows the user to connect and control a Digital Torque Wrench to be used in assembly production
- Wrench can be paired to the TCI with a single button press
- Easy management, setup and diagnostics of itself via Web Browsers
- Can be used stand alone, jobs can be selected and result sent to a PC or webpage
- Accepts Open Protocol commands via Ethernet to select a job to use with the WrenchStar Multi
- Web Status page allows Ethernet properties, RF properties, logging of messages, and Wrench status to be monitored
- Web Page mirrors last Torque and Angle reading from Wrench plus it's Torque status (LO, OK and HI)
- 360° LED lights show real time status of the Wrench connection on the unit
TCI [Tool Controller Interface] Technical Specifications:
- Operating temp range: -20 to +50°C
- Storage temp range: -20 to +50°C
- Humidity: 10-75% non-condensing
- IP Rating: IP40 (indoor use only)
- Job storage: 20 Jobs
- Power: 5V +/-10% DC power supply 1000mA OR Mini Type-B
- Ethernet: RJ45 socket
- Serial: 9-way D-type RS232 socket for serial connection to a PC in standalone
- USB: Mini USB Cable for programming firmware
- RF: 2.4GHz antenna for RF Wrench communication
  Low-power 0dBm and uses worldwide ISM band (2400MHz).
- Dimensions: 217mm x 120mm x 56mm
- LEDs: Power status
  Host (communications are good, absent or incorrect).
  Wrench (informs WrenchStar Multi is paired, in range or has a Job loaded)
- Operation: Open Protocol commands via Ethernet to select a Job and use with the Wrench
  Standalone mode – Jobs can be selected and results posted to PC or web page.

Sales Code | Description
---|---
TCIAB-0000-CRXXR1 | TCI – Single wrench

- Colour coded result monitoring
- Easy Job setup via web Browser
- Open Protocol compatible
- and many more...

For more Information about the TCI Lineside Controller or for a quote, get in touch with us on +44 (0)1455 25 14 88
or email us at sales@crane-electronics.com.

Crane, the force in torque management

TCI controller datasheet [13]