Department of Electrical Power Engineering and Mechatronics

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.

"......." 2019

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Thesis is in accordance with terms and requirements

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Department of Electrical Power Engineering and Mechatronics

THESIS TASK

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Thesis topic:

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 varasemaid 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:

No	Task description	Deadline
1.	Thesis proposal	18.2.2019
2.	Selection of torque tool	20.2.2019
3.	Analyzing risks caused by poor connection	2.4.2019
4.	Testing tools from assembly site	23.4.2019
5.	Presenting draft version to supervisors	3.5.2019

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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 [4].

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 [4].

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 [4].

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

1.2 Recommendations when torqueing 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 [5].

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 arching 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 arching. 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.

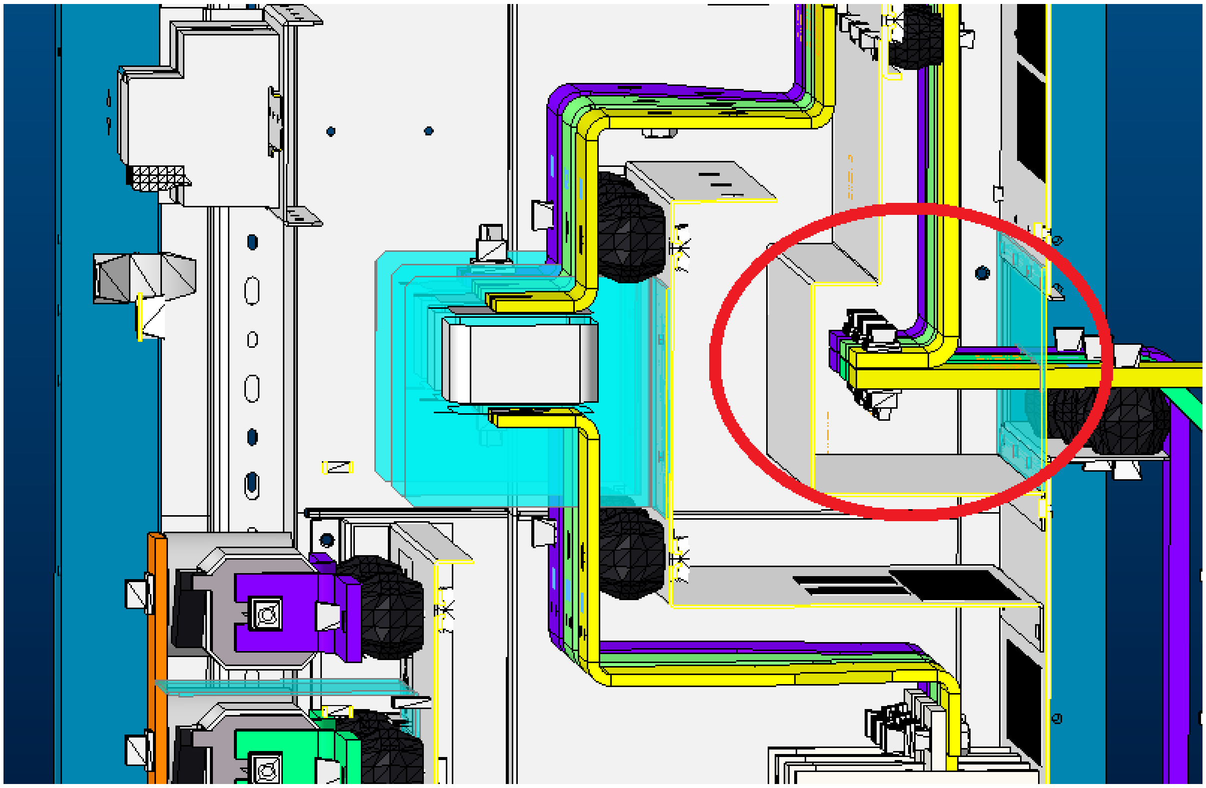

Figure 3. Connection is located in the back area of the final prduct

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).

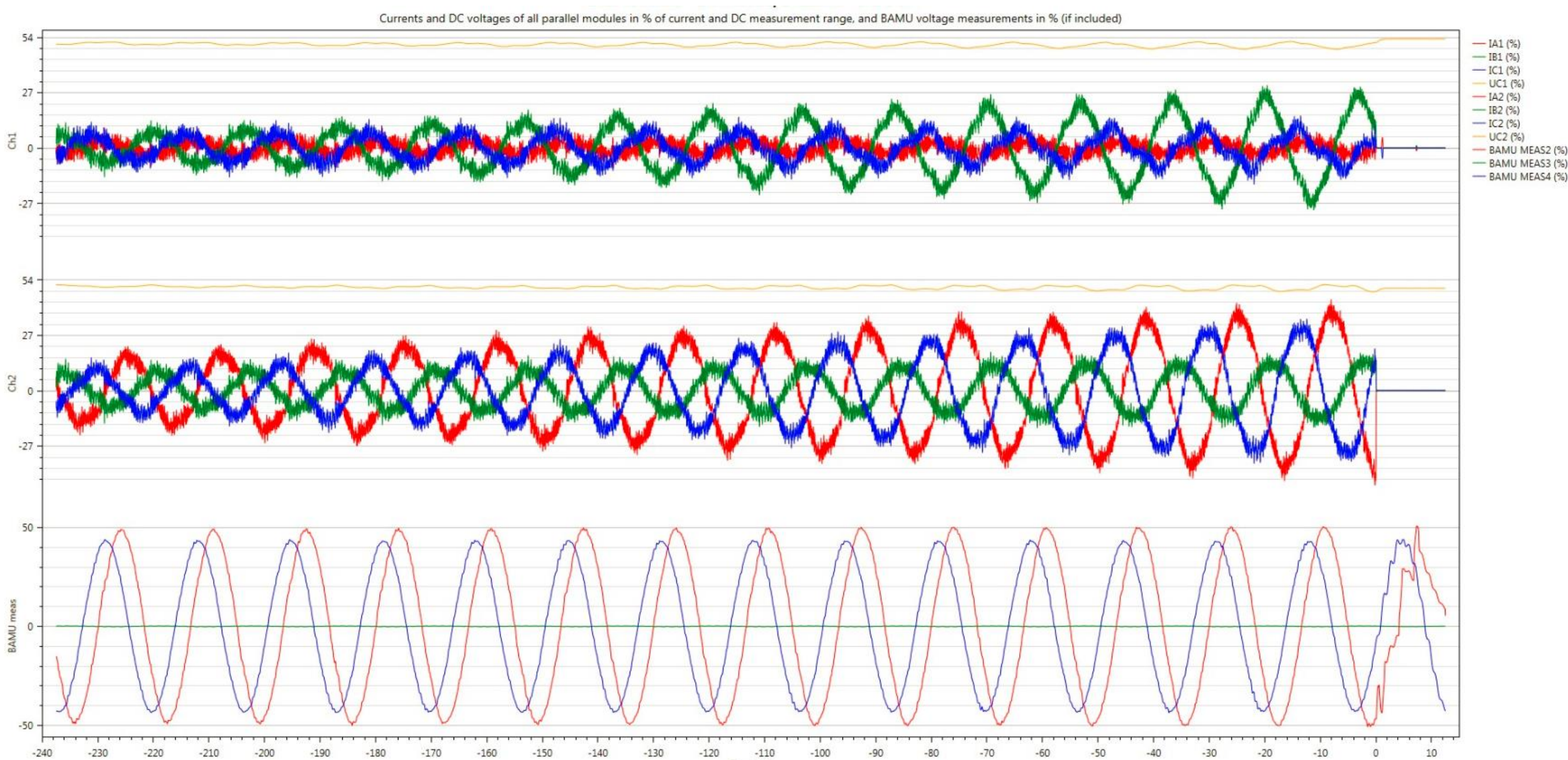

Figure 4. Current flow differences between phases

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.

Figure 8. Damaged bolts and nuts

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 connetions 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

Combi screw/bolt	Elect. Connection Nm			Note!
M3	0.5			Strength class 4.6 ... 8.8
M4	1			Strength class 4.6 ... 8.8
M5	4			Strength class 8.8
M6	9			Strength class 8.8
M8	22			Strength class 8.8
M10	42		See exceptions	Strength class 8.8
Hexagon bolt	Elect. Connection Nm			Note!
M6	9			Strength class 8.8
M8	22			Strength class 8.8
M10	42		See exceptions	Strength class 8.8
M12	70		See exceptions	Strength class 8.8
M16	120		See exceptions	Strength class 8.8
Torx screw	Elect. Connection Nm		Mechanical Nm	Note!
M6	5		5	Frame earthling/mech.
Set screw for fuses	Bussman Nm	Ferraz S. Nm	Set screw to fuse Nm	Note!
M8	20	13.5	Max 5	Strength class 8.8
M10	40	26	Max 5	Strength class 8.8
M12	50	46	Max 5	Strength class 8.8
Cable shoe	Elect. Connection Nm			Note!
M8	15			Strength class 8.8
M10	32			Strength class 8.8
M12	50			Strength class 8.8
Exceptions	Elect. Connection Nm		Mechanical Nm	Note!
M6 Serpress	5			Strength class 8.8
M8 Serpress	15			Strength class 8.8
M10 Serpress	35			Strength class 8.8
M10 Combi Screw	10			LCL-capacitor
M16 Hexagon bolt	80			LCL-reactor bus bar
M16 Hexagon bolt			70	Lifting bar
M12 Fastening			10	B25834-S7826-K**4-1 Capacitor (Sine filter)
M10 Elec. Terminal	7			
M6 Fastening			5	SKK81/22 ja 192/22 Diode (LC Charging)
M5 Elec. Terminal	3			
M6 Elec. Terminal	5			

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.

Sub item Sub function	Requirements	Potential Failure Mode	Potential Effects of Failure C - Customer P - Process	SEV	Potential Causes	Current Process Controls - Prevention	OCC	Current Process Controls - Detection	DET	RPN	Re-commended action(s)
Electrical connection: Fasteners	Fastener - *Nm* M3 - 0.5...0.8 M4 - 1...2 M5 – 4 M6 - 9 M8 – 22 M10 - 42 M12 – 70 M16 - 120 Exception: M10 - 10 LCL capacitor Exception: M16 - 80 LCL- bus bars	Too high torque	C -Loose connection due to subsequent fracture of screw. Bus bar connection overheats on the field. Arc flash. Fire inside the product.	9	1. Calibration process 2. Wrong tool used 3. Tool is broken 4. Overtightening with manual wrench	1. Assembly Manuals 2. Calibrated tools 3. Preventive maintenance	3	No check	10	270	New check system should be implemented
Electrical connection: Fasteners	Fastener - *Nm* M3 - 0.5...0.8 M4 - 1...2 M5 – 4 M6 - 9 M8 – 22 M10 - 42 M12 - 70 M16 - 120 Exception: M10 - 10 LCL capacitor Exception: M16 - 80 LCL- bus bars	Too low torque	C - Bus bar connection overheats on the field. Arc flash. Fire inside the product.	9	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)	1. Assembly manuals 2. Calibrated tools 3. Preventive maintenance	3	Double check with tools	9	243	New check system should be implemented

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 *Nm*. 20 *Nm* tools were chosen thanks to relatively small error compared to tools that have higher nominal torque values (i.e. 70 *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 *mm*)
- Sheet metal plate (thickness 1,5 *mm*)
- Metal plate (thickness 3 *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.

The tool corresponds to EN ISO 678:2003 standard.

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	=	$Measurement \pm Absolute\ error$
Absolute error	=	$Accuracy\ error + Reading\ error$
Accuracy error	=	$Measurement\ \cdot \frac{Accuracy}{100}$
Reading error	=	$Units\ reading\ error\ \cdot Lowest\ unit\ on\ display$

From datasheet: Absolute error = $\pm\ 1\% - k = 2$

$$\pm\ \frac{1}{100} \cdot 20 - 1\ \cdot 0{,}01 =\ \pm 0{,}20 - 0{,}01$$

Relative error

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

Uncertainty of Holex test equipment if 20 *Nm* is set as nominal value

$$\boldsymbol{x_{t0} =\ x_0 +\ \Delta x_{1-a} = 20{,}00\ \pm\ 0{,}20\ Nm}$$

3.1.3 Air compressed tools

1) Air tool 1 - Atlascopco EP6PTX32 HR10-AT, serial number 7673; Manufacturing year - 2014; Torque range 15 – 32 *Nm* at pressure 6,3 *bar*. Next calibration: W25 2019

Figure 13. Typical air tool used on assembly line

	Nominal value	Measured value
Test No.	*Nm*	*Nm*
1	20 +- 10 %	17,34
2	20 +- 10 %	21,02
3	20 +- 10 %	19,41
4	20 +- 10 %	21,74
5	20 +- 10 %	18,29

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

$$u_{RE} = \frac{{}^{1}\!/_{2}\ Smallest\ digital\ reading}{\sqrt{3}} = \frac{0,5 \cdot 0,01}{\sqrt{3}} \approx 0,0029$$

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

$$\Delta x_{1-a} = k \cdot u = 2 \cdot 1,2741 = 2,5482 \approx 2,55\ Nm$$

Average value

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

Final tool accuracy

$$\boldsymbol{x_{t\ Air1} = x_0 + \Delta x_{1-a} = 19,56 \pm 2,55\ Nm}$$

2) Air tool 2 - Atlascopco EP6PTS22 HR10-RE, serial number 6194; Manufacturing year - 2013; Torque range 10 -22 *Nm* at pressure 7.0 *bar*. Next calibration: W25 2019

	Nominal value	Measured value
Test No.	*Nm*	*Nm*
1	20 +- 10 %	23,04
2	20 +- 10 %	24,05
3	20 +- 10 %	23,66
4	20 +- 10 %	24,39
5	20 +- 10 %	24,07

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

$$u_{RE} = \frac{1/2 \ Smallest\ digital\ reading}{\sqrt{3}} = \frac{0{,}5 \cdot 0{,}01}{\sqrt{3}} \approx 0{,}0029$$

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

$$u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0{,}1)^2 + (0{,}3897)^2 + (0{,}0029)^2 + 0 + 0} \approx 0{,}1627$$

$$u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0{,}1627^2} = 0{,}1627$$

Measurement uncertainty

$$\Delta x_{1-a} = k \cdot u = 2 \cdot 0{,}1627 = 0{,}3254 \approx 0{,}33\ Nm$$

Average value

$$x_0 = \frac{\sum x_i}{n} = \frac{(23{,}04 + 24{,}05 + 23{,}66 + 24{,}39 + 24{,}07)}{5} = 23{,}84\ Nm$$

Final tool accuracy

$$\boldsymbol{x_{t\ Air2} = x_0 + \Delta x_{1-a} = 23{,}84 \pm 0{,}33\ Nm}$$

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

	Given value	Measured value
Test No.	*Nm*	*Nm*
1	20 +- 10 %	21.78
2	20 +- 10 %	21.33
3	20 +- 10 %	22.12
4	20 +- 10 %	21.18
5	20 +- 10 %	22.28

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

$$u_{RE} = \frac{1/2 \; Smallest \; digital \; reading}{\sqrt{3}} = \frac{0,5 \cdot 0,01}{\sqrt{3}} \approx 0,0029$$

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

$$u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0,1)^2 + (0,3175)^2 + (0,0029)^2 + 0 + 0} \approx 0,3329$$

$$u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0,3329^2} = 0,3329$$

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

$$\boldsymbol{x_{t\,regular} = x_0 + \Delta x_{1-a} = 21,74 \pm 0,67 \; Nm}$$

3.1.5 Atlascopco Saltun SWR-30 torque wrench

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

Figure 15. Atlascopco torque wrench

	Nominal value	Measured value
Test No.	*Nm*	*Nm*
1	20 +- 10 %	20,05
2	20 +- 10 %	19,53
3	20 +- 10 %	19,47
4	20 +- 10 %	19,82
5	20 +- 10 %	19,41

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

$$u_{RE} = \frac{{}^{1}\!/_{2}\ Smallest\ digital\ reading}{\sqrt{3}} = \frac{0{,}5 \cdot 0{,}01}{\sqrt{3}} \approx 0{,}0029$$

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

$$u_B = \sqrt{u_{ST}^2 + u_R^2 + u_{RE}^2 + u_{MET}^2 + u_{ENV}^2} = \sqrt{(0{,}1)^2 + (0{,}1847)^2 + (0{,}0029)^2 + 0 + 0} \approx 0{,}2101$$

$$u = \sqrt{u_A^2 + u_B^2} = \sqrt{0 + 0{,}2101^2} = 0{,}2101$$

Measurement uncertainty

$$\Delta x_{1-a} = k \cdot u = 2 \cdot 0{,}2101 = 0{,}4202 \approx 0{,}42\ Nm$$

Average value

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

Final tool accuracy

$$\boldsymbol{x_{t\ Atlascopco} = x_0 + \Delta x_{1-a} = 19{,}66 \pm 0{,}42\ Nm}$$

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

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

Figure 17. Various head types used with MultiStar torque wrench

Figure 18. Installed chip in head

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 and real easy task.

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

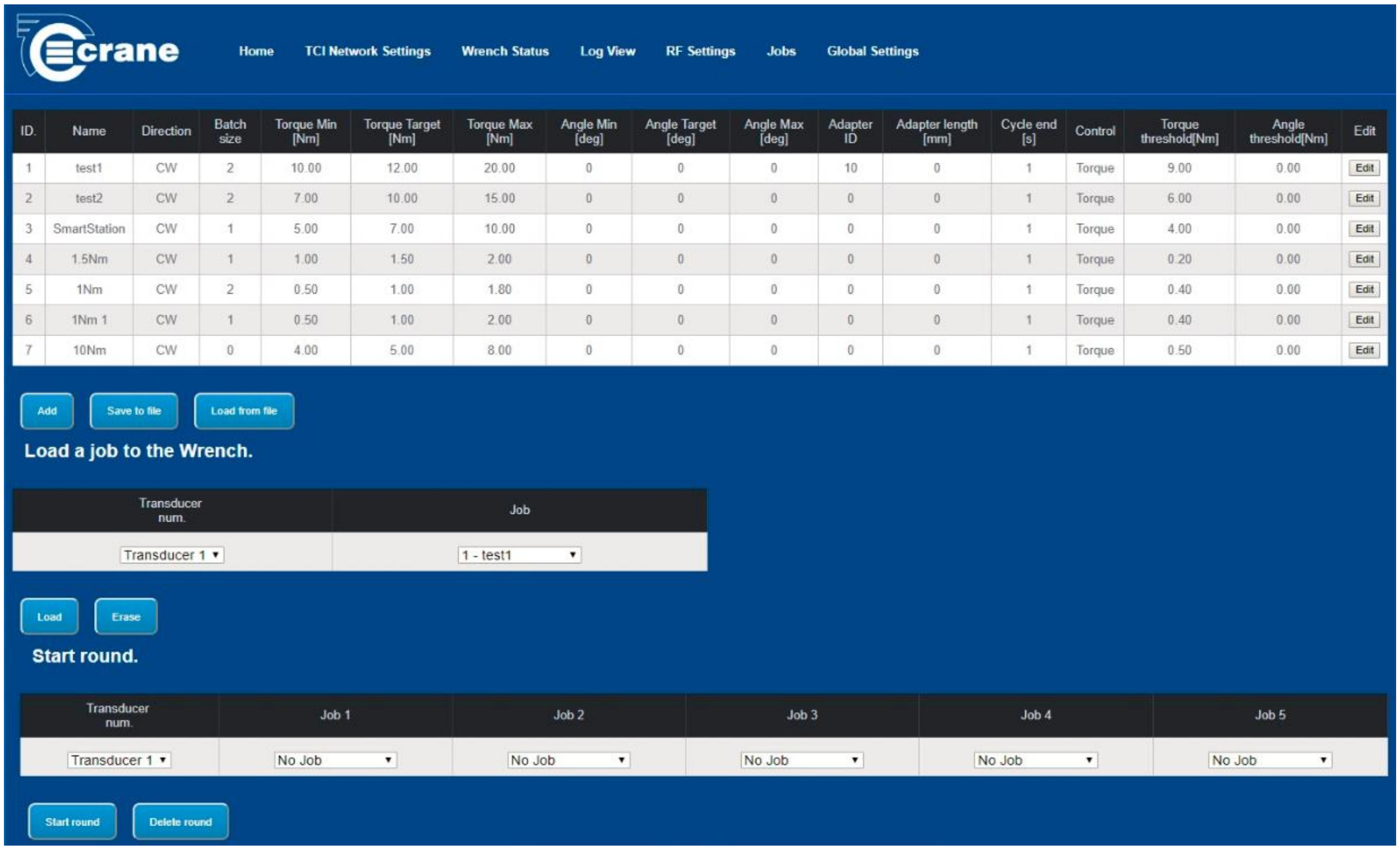

Figure 20. Setting up torque values to wrench heads

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.

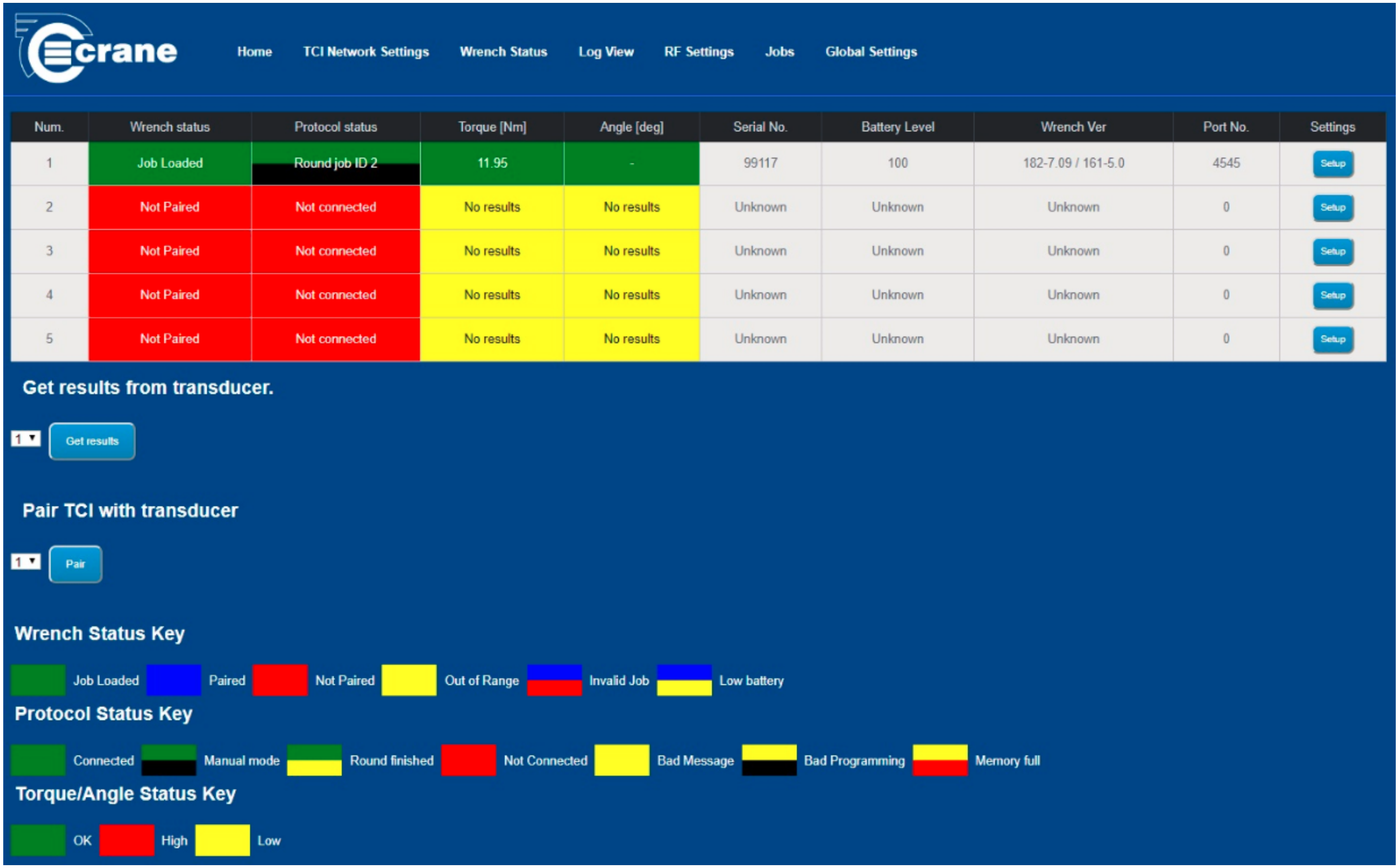

Figure 21. Result (Protocol Status) is shown on PC screen

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

Figure 24. WrenchStar Multi Torque wrench

	Nominal value	Actual value	Measured value
Test No.	*Nm*	*Nm*	*Nm*
1	20 +- 10 %	19,18	18,83
2	20 +- 10 %	20,59	20,32
3	20 +- 10 %	20,11	19,47
4	20 +- 10 %	19,91	19,53
5	20 +- 10 %	21,45	20,72

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

$$u_{RE} = \frac{{}^{1}/_{2} \ Smallest\ digital\ reading}{\sqrt{3}} = \frac{0{,}5 \ \cdot 0{,}01}{\sqrt{3}} \approx 0{,}0029$$

Measurement error caused by metrology error

$$u_{MET} = 0$$

Measurement error caused by environment change

$$u_{ENV} = 0$$

Process variation

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

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

$$= \sqrt{\frac{1}{20} \cdot (1{,}14 + 0{,}1169 + 0{,}019 + 0{,}1142 + 1{,}4445)} \approx 0{,}3765$$

Measurement variation

$$u_B = \sqrt{u_{ST}^2 \ + \ u_R^2 + \ u_{RE}^2 \ + \ u_{MET}^2 \ + \ u_{ENV}^2} \ = \ \sqrt{(0{,}1)^2 + \ (0{,}5456)^2 + \ (0{,}0029)^2 + 0 + 0} \approx\approx 0{,}3077$$

$$u = \sqrt{u_A^2 + \ u_B^2} = \sqrt{0{,}3765^2 + \ 0{,}3077^2} = \sqrt{0{,}2364} \approx 0{,}4862$$

Measurement uncertainty

$$\Delta x_{1-a} = k \ \cdot \ \ u = 2 \ \cdot 0{,}4862 = 0{,}9724 \ \approx 0{,}97 \ Nm$$

Average value

$$x_0 = \frac{\sum x_i}{n} = \frac{(18{,}83 + 20{,}32 + 19{,}47 + 19{,}53 + 20{,}72)}{5} = 19{,}77 \ \ Nm$$

Final tool accuracy

$$\boldsymbol{x_{t\,WrenchMulti} = \ x_0 + \ \Delta x_{1-a} = 19{,}77 \ \pm \ 0{,}97 \ Nm}$$

4. Comparsion of the tools

4.1 Metrics

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

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

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 *.

	Price	Required Quantity	Additional equipment price **	Required Quantity	Total cost
Tool	*EUR*	*Pc*	*EUR*	*Pc*	*EUR*
Atlascopco Air tool	3669.68	1	32.62	1	3724.05
			21.75	1	
Regular racket head torque wrench	231.05	1	-	-	231.05
Atlascopco racket head torque wrench	475.70	1	21.75	1	497.45
WrenchStar Multi Torque tool	3608.68	1	1718.06	1	5478.96
			152.22	1	

Table 9. Cost of tools

* 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.

$$Cost_{Now} = 7 \cdot Regular\ torque\ wrench + 3 \cdot Atlascopco\ torque\ wrench\ (with\ extra\ equipment)$$
$$= 7 \cdot 231{,}05 + 3 \cdot (475{,}70 + 21{,}75) = 3174{,}95\ €$$

$$Cost_{MultiWrench} = Torque\ tool + TCI + 3 \cdot Heads = 3608{,}68 + 1718{,}06 + 3 \cdot 152{,}22 = 5783{,}40\ €$$

$$Expenses = Cost_{MultiWrench} - Cost_{reg} = 5783{,}40 - 3174{,}95 = 2608{,}45\ €$$

Figure 25. Current tool set what is planned to be replaced

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.

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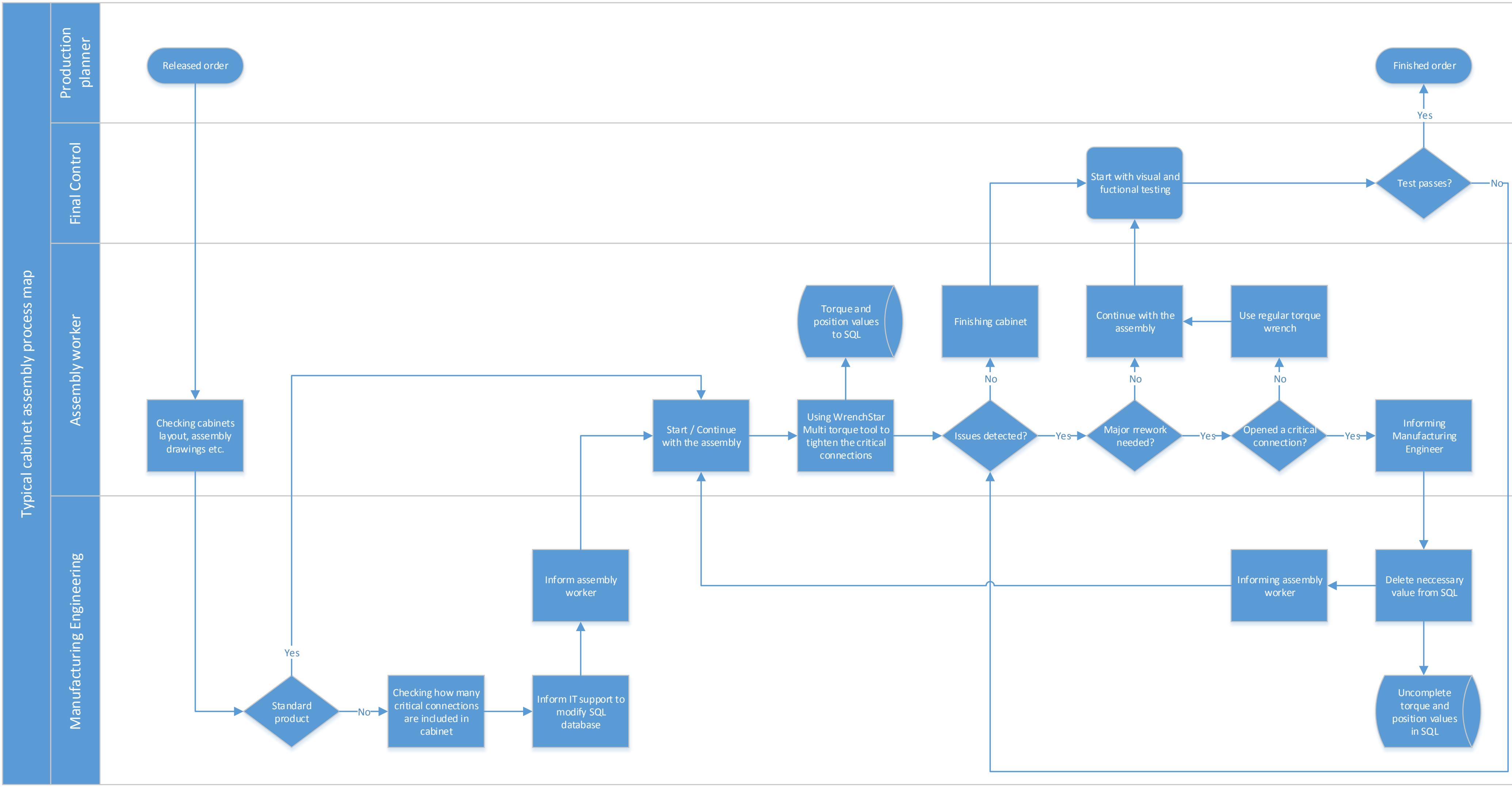
Typical cabinet assembly process map
Production planner
Final Control
Assembly worker
Manufacturing Engineering
Released order
Finished order
Yes
Test passes?
No
Start with visual and fuctional testing
Torque and position values to SQL
Finishing cabinet
Continue with the assembly
Use regular torque wrench
No
No
No
Checking cabinets layout, assembly drawings etc.
Start / Continue with the assembly
Using WrenchStar Multi torque tool to tighten the critical connections
Issues detected?
Yes
Major rework needed?
Yes
Opened a critical connection?
Yes
Informing Manufacturing Engineer
Inform assembly worker
Informing assembly worker
Delete neccessary value from SQL
Yes
Standard product
No
Checking how many critical connections are included in cabinet
Inform IT support to modify SQL database
Uncomplete torque and position values in SQL

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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APPENDIX

Appendix 1 – Severity

SEVERITY (Based on AIAG FMEA 4th edition)				
Effect	**Criteria: Severity of effect on Product (Customer Effect)**	**Rank**	**Effect**	**Criteria: Severity of effect on Product (Customer Effect)**
Failure to Meet Safety and/or Regulatory Requirements	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10	**Failure to Meet Safety and/or Regulatory Requirements**	May endanger operator (machine or assembly) without warning
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	9		May endanger operator (machine or assembly) with warning
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).	8	**Major Disruption**	100% of product may have to be scrapped. Line shutdown or stop ship.
	Degradation of primary function (vehicle operable, but at reduced level of performance).	7	**Significant Disruption**	A portion of the production run may have to be scrapped. Deviation from primary process including decreased line speed or added manpower.
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable)	6	**Moderate Disruption**	100% of production run may have to be reworked off line and accepted.
	Degradation of secondary function (vehicle operable, but comfort/convenience functions inoperable).	5		A portion of the production run may have to be reworked off line and accepted.
Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (>70%).	4	**Moderate Disruption**	100% of 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 many customers (50%).	**3**		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%).	**2**	**Minor Disruption**	Slight inconvenience to process, operation, or operator.
No effect	No discernible effect.	**1**	**No effect**	No discernible effect.

Table 10. Severity scale

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

Appendix 2 – Occurrence

OCCURANCE

Like hood of Failure	Criteria: Occurrence of cause - PFMEA (Incidents per items/vehicles/opportunities)	Failure rate	Rank
Very High	>= 100 per thousand >= 1 in 10	Every day	10
High: repeated failures	50 per thousand 1 in 20	Once per 2-3 days	9
	20 per thousand 1 in 50	Once in a week	8
	10 per thousand 1 in 100	Once in a month	7

Moderate: occasonal failure	2 per thousand 1 in 500	Once in 3 months	6
	0,5 per thousand 1 in 2000	Once in 6 months	5
	0,1 per thousand 1 in 10000	Once in a year	4
Low: relatively few failiures	0,01 per thousand 1 in 100000	Once in 1-3 years	3
	<= 0,001 per thousand 1 in 1000000	Once in 3-5 years	2
Remote: failure is unlikely	Failure is eliminated through preventive control		1

Table 11. Occurrence scale

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

Appendix 3 – Detection

Detection

Opportunity for detection	Criteria: Like hood of Detection by Process Control	Inspection			Rank	Likehood of Detection
		A	B	C		
No detection opportunity	Absolute of certainty of non-detection: 1. No current process control; 2. Cannot detect or is not checked				10	Allmost Impossible
Not likely to detect at any stage	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)			x	9	Very remote
Problem Detection Pos Processing	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			x	8	Remote
Problem Detection at Source	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.)			x	7	Very Low
Problem Detection Post Processing	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.)		x	x	6	Low
Problem Detection at Source	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)		x		5	Moderate
Problem Detection Post Processing	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.	x	x		4	Moderately High

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	x	x		3	High
Error Detection and/or Problem Preventio n	Controls almost certain to detect: 1. Error defection 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	x	x		2	Very High
Detection not applicable ; Error Preventio n	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.	x			1	Almost Certain

Inspection types:

A	Error-proofed (in-line100% inspections)
B	Testers
C	Manual Inspection (visual testing, common testing methods)

Table 12. Detection scale

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

Appendix 4 – Torque wrench and TCI datasheets

Crane Electronics Ltd
The force in torque management

The WrenchStar Multi - Production Wrench

- The WrenchStar Multi Digital Torque Wrench is for customers who require Torque and Angle Data digitally recording.
- Includes a **360º 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.

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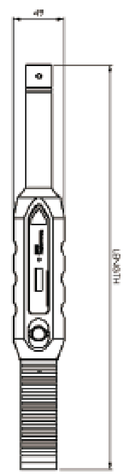
crane

WrenchStar Multi Technical Specifications:

Operating temp range:	-20 to +50ºC.
Storage temp range:	-20 to +50ºC.
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/ºC.
Static Accuracy:	±0.25% FSD.
Angle Measurement:	Sample every 1000 micro seconds.
Frequency Response:	75Hz to 4608Hz.
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.

Sales Code WSM plus Battery and Cradle	Range	Insert	Weight (gr)	Length (mm)
WS1JX-0010-C1DARX	10Nm DIN Insert	9X12 mm	833	380
WS1AX-0010-C1FARX	10Nm Fixed Head		720	330
WS1JX-0025-C1DARX	25Nm DIN Insert		904	380
WS1AX-0025-C1FARX	25Nm Fixed Head		725	330
WS1JX-0075-C1DARX	75Nm DIN Insert		914	395
WS1JX-0120-C1DARX	120Nm DIN Insert		967	395
WS1KX-0180-C1DARX	180Nm DIN Insert	14x18 mm	1474	613
WS1KX-0250-C1DARX	250Nm DIN Insert		1710	640
WS1KX-0340-C1DARX	340Nm DIN Insert		1925	788
WS1KX-0500-C1DARX	500Nm DIN Insert		3173	887
WS1DX-0750-C1FARX	750Nm Fixed Head	Fixed	5279	1178
WS1FX-1000-C1FARX	1000Nm Fixed Head		8527	1433
WS1FX-1500-C1FARX	1500Nm Fixed Head		10377	1921



Interchangeable ID Heads also available

UK05/2017v1 - WSM

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, set up and diagnostics of itself via Web Browsers
- Can be used **stand alone**, jobs can be selected and results 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

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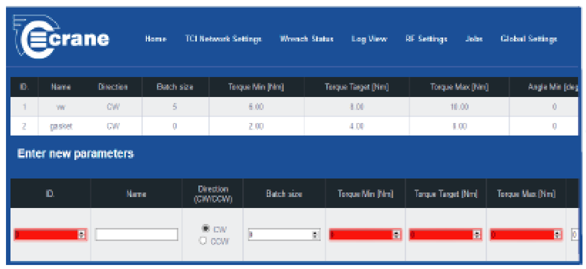
TCI (Tool Controller Interface) Technical Specifications:	
Operating temp range:	-20 to +50°C
Storage temp range:	-20 to +50°C
Humidity:	10-75% non-condensing
IP Rating:	IP40 (Indoor use only)
Job storage:	20 Jobs
Power:	5V +/-10% DC power supply 1000mA OR Mini Type-B
Ethernet:	RJ45 socket
Serial:	9-way 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
TC1AB-0000-CRXXR1	TCI – Single wrench



UK11/2017v1 - TCI

- ✓ 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.

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TCI controller datasheet [13]