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Framework for Continuous Improvement of Production Processes

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This research introduces a new approach of using Six Sigma DMAIC (Define, Measure, Analyse, Improve, Control) methodology. This approach integrates various tools and methods into a single framework, which consists of five steps. In the Define step, problems and main Key Performance Indicators (KPIs) are identified. In the Measure step, the modified Failure Classifier (FC), i.e. DOE-NE-STD-1004-92 is applied, which enables to specify the types of failures for each operation during the production process. Also, Failure Mode and Effect Analysis (FMEA) is used to measure the weight of failures by calculating the Risk Priority Number (RPN) value. In order to indicate the quality level of process/product the Process/Product Sigma Performance Level (PSPL) is calculated based on the FMEA results. Using the RPN values from FMEA the variability of process by failures, operations and work centres are observed. In addition, costs of the components are calculated, which enable to measure the impact of failures on the final product cost. A new method of analysis is introduced, in which various charts created in the Measure step are compared. Analysis step facilitates the subsequent Improve and Control steps, where appropriate changes in the manufacturing process are implemented and sustained. The objective of the new framework is to perform continuous improvement of production processes in the way that enables engineers to discover the critical problems that have financial impact on the final product. This framework provides new ways of monitoring and eliminating failures for production processes continuous improvement, by focusing on the KPIs important for business success. In this paper, the background and the key concepts of Six Sigma are described and the proposed Six Sigma DMAIC framework is explained. The implementation of this framework is verified by computational experiment followed by conclusion section.

Keywords: *Failure Classifier (FC), Failure Mode and Effect Analysis (FMEA), Process/Product Sigma Performance Level (PSPL), Failure Cost Calculation (FCC), Cost Weighted Factor for Risk Priority Number (CWFRPN).*

Introduction

In order to be competitive and successful on the market place and satisfy customers, companies should continuously improve their production processes and product quality. The features of reliable and stable production process: less scrap, less rework, less the consumption of additional recourses, time and money.

From the literature review of the various sources that describe the scientific achievements made in the field of FMEA and Six Sigma, it can be summarised that the main goal of these methods is continuous improvement of business processes. Initially, researchers used these methods independently in order to achieve their goals. However, later, researchers started to combine these methods in order to achieve results that are more efficient.

Initially the Six Sigma methodology was developed for elimination of variability, and lean manufacturing for elimination of wastes in business processes (Womack *et al.*, 1990; Womack & Jones, 1994). Later, these methodologies have been combined with DMAIC method for structural approach of problem solving. This combination later became known as Lean Six Sigma (Aon Management Consulting, 2003; Brook, 2010). There are many different tools that are used in Lean Six Sigma, such as FMEA, Value Stream Mapping, Cause & Effect, Design of Experiments (DOE), SIPOC/COPIS, QFD/House of Quality and others (Brook, 2010). These methods are developed for various purposes, such as, measurement, analysis and improvement of business processes. But the most suitable Lean Six Sigma tool that intended to improve the reliability of business processes is FMEA (MacDermott *et al.*, 1996). There are large amount of research papers where discussed common application of FMEA and Six Sigma for attainment of specific goals (Mekki, 2006; Krishna & Dangayach, 2007; Sarkar, 2007; Yang *et al.*, 2010; Bhanumurthy, 2012; Chiarini, 2012). Based on comprehensive literature review results, it is possible to discover what achievements have not yet been done by combining these methodologies together:

- Calculate Sigma performance level that shows the level of process or product quality based on the data from FMEA.
- Calculate the financial impact of failure, in the process, on the final product cost using the data from FMEA.

Such approaches can enable to the engineers determine more efficiently failures which influence on KPIs, analyse and improve them. All these questions will be discussed further in the current paper.

The reason for selection of Six Sigma DMAIC methodology in current research, because today it is well-known methodology used in many companies around the world. However, every company can apply presented approach in another well-known methodology like PDCA, 8D or 4Q (Sahno & Shevtsenko, 2014).

Research Objectives and Scope

The objective of this research is to develop the framework for continuous improvement of reliability of production processes that allows improving KPIs - product Quality and Cost. This framework should integrate various quality improvement tools and methodologies. The new framework will be applied in rigorous Six Sigma DMAIC methodology that enables to define, measure, analyse improve and control problematic production process.

This framework helps engineers to find problematic operations and eliminate root causes of problems quickly and with less effort. The framework would play the role of a “dashboard” like in a cockpit, which allows monitoring the specified indicators such as Process/Product Sigma Performance Level (PSPL) and Cost Weighted Factor for RPN (CWF_{RPN}). These subsequently influence Quality KPI and Cost KPI in an up-to-date way due to the constantly renewed data from production floor, for example, data from Enterprise Resource Planning (ERP) system (Umble *et al.*, 2003).

The framework is oriented towards the improvement of production processes in production floor, it is suitable for SMEs and can be applied in big enterprises, which have batch production.

Key Concepts Applied in the Research

This section provides the background of basic concepts and definitions that have been used in this research.

Key Performance Indicators (KPIs). KPI is a measure of performance; it is very useful for evaluating the current status of a company and for foreseeing the possible benefits of adopting an innovation in the system. KPIs are quantifiable measurements and depend on the particular company, which would evaluate those (Barchetti *et al.*, 2011). Performance measurement is a fundamental principle of management and it is important because it identifies the gaps between current and desired performance, also provides indication of progress towards closing the gaps. Carefully selected KPIs identify precisely where to take action to improve performance (Weber *et al.*, 2005).

Production Route (PR) card. It is a card that gives the detail of an operation to be performed in a production line. It is used to instruct the production people to take up the production work. The content and formats of the PR card can vary from a company to company. In general, it contains: an item and the number of quantities to be produced; production time; dimensions; any additional information that may be required by the production worker. PR card traces the route to be taken by a job during a production process (PR card 09.2013).

Failure Mode and Effect Analysis (FMEA). It is a systematic method of identifying and preventing product and process problems before they occurred. In recent years, companies are using FMEA to enhance the reliability and quality of their products and processes (Johnson 1998). The risk of a failure and its effects in FMEA are determined by three factors:

- *Severity (S)* – the consequence of a failure that might occur during process.
- *Occurrence (O)* – the probability or frequency of that failure occurring.
- *Detection (D)* – failure being detected before the impact of the effect realized.

Every potential failure mode and cause is rated in these three factors on a scale ranging from 1 to 10. By multiplying these rating (See Equation 1), a Risk Priority Number (RPN) is generated. This RPN is used to determine the effect of a failure.

$$RPN = S \times O \times D \qquad (1)$$

The RPN ranges from 1 to 1000 for each failure mode. It is used to rank the need for corrective actions to eliminate or reduce the potential cause of failures (MacDermott *et al.*, 1996). All FMEAs are team based and the purpose of FMEA team is to bring a variety of perspectives and experience to the project (Stamatis, 2003).

Failure Classifier (FC). Reliability engineering deals with an analysis of the causes of the faults in factories. In this paper a Failure Classifier (FC) is developed based on DOE-NE-STD-1004-92 standard, shown in Figure 1. There are seven major cause categories, and each has its subcategories. The basic goal of using this standard is to define the problems or causes that might occur for each operation during production process, in order to further correct them (DOE-NE-STD-1004-92, 09.2013). This standard was adapted and modified for the machinery enterprises (Karaulova *et al.*, 2012).

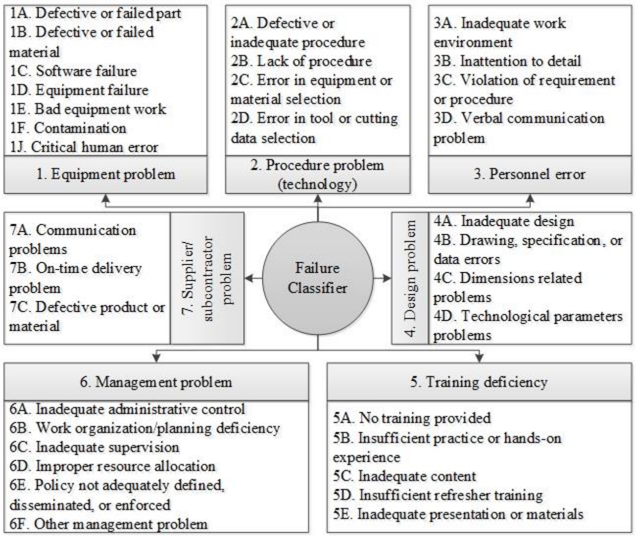


Figure 1. Failure Classifier

Six Sigma DMAIC. Six Sigma utilizes analytical tools and processes to measure quality and eliminate variances in processes. The objective of Six Sigma is to produce near perfect products and services that will satisfy customers

(Stephens *et al.*, 2007). Motorola was the first company who launched a Six Sigma project in the mid-1980s (Rancour *et al.*, 2000). Since then, the applications of the Six Sigma methods allowed many organizations to sustain their competitive advantage by integrating their knowledge of the process with statistics, engineering, and project management (Anbari, 2002). It is a project-driven management approach intended to improve the products, services and processes of organizations by reducing defects. It is a business strategy that focuses on improving customer requirements understanding, business systems, productivity, and financial performance (Kwak *et al.*, 2006; Desai *et al.*, 2008). Six Sigma's DMAIC method offers a thorough roadmap for analysis and diagnosis of problems; driven by powerful tools and techniques (Van Den Heuvel *et al.*, 2006). The steps of the Six Sigma DMAIC are described in this section.

- *Define* step is where a problem is identified and quantified in terms of the perceived result. The product and/or process to be improved are identified, resources for the improvement project are put in place and expectations for the improvement project are set.
- *Measure* step enables to understand the present condition of its work process before it attempts to identify where they can be improved. The critical to-quality characteristics are defined and the defects in the process/product developed through graphical analysis. All potential effects on failure modes are identified.
- *Analyse* step adds statistical strength to problem analysis, identifies a problem´s root cause and determines how much of the total variation is.
- *Improve* step aims to develop, select and implement the best solutions with controlled risks. The effect of the solutions that are then measured with the KPI developed during the Measure step.
- *Control* step is intended to design and implement a change based on the results made the Improve step. This step involves monitoring the process to ensure it works according to the implemented changes, capture the estimated improvements and sustain performance (Watson, 2004).

From the statistical point of view, the term Six Sigma is defined as having less than 3,4 Defects Per Million Opportunities (DPMO) or a success rate of 99,9997 %, where sigma is a term used to represent the variation about the process average (Antony *et al.*, 2002). If a company is operating at three sigma levels for quality control, this is interpreted as achieving a success rate of 93,32 % or 66807 DPMO. Therefore, the Six Sigma method is a very rigorous quality control concept, where many organizations still performs at three sigma levels (McClusky 2000). Today, to calculate DPMO, it is used the following Equation 2 (Seemer, 2010) and sigma performance scale table presented in Table 1, which enables to define Process/Product Sigma Performance Level on the basis of DPMO or process yield.

$$DPMO = \frac{\sum D \times 1000000}{\sum U \times \sum O} \tag{2}$$

where:

DPMO – product sigma performance level or DPMO level;

ΣD – sum of real defects occurred;

ΣU – sum of units produced/tested;

ΣO – sum of opportunities for defects per unit.

It can take a long time for a company to produce a million of items, but it is not so important; this scale is just a projection of the number that would happen if a company will produce this amount. To define on what sigma performance level company operates, it can be identified the percentage of the Process Yield (PY) (see Equation 3) and defined the corresponding sigma level in the sigma scale table (Six Sigma, 15.01.2015).

$$PY = \frac{\sum O - \sum D}{\sum O} \times 100 \tag{3}$$

Table 1

Sigma performance scale table (Watson, 2004)

Sigma Performance Level	Defects per Million Opportunities (DPMO)	Process Yield
1,0 δ	670000	33 %
2,0 δ	308537	69,2 %
2,78 δ	100000	90 %
3,0 δ	66807	93,32 %
4,0 δ	6210	99,38 %
5,0 δ	233	99,9767 %
6,0 δ	3,4	99,99966 %

Six Sigma DMAIC framework

This section presents the new framework for continuous improvement of reliability of production process and KPIs. Proposed framework is presented in Figure 2 that shows the Quality-Cost (QC) framework in Six Sigma DMAIC structure. The details of the framework is explained below.

Define. The problematic process should be defined and the required KPI metric(s) for continuous improvement must be evaluated and indicated.

Measure. In Measure step, three different tools/methods are applied: 1) Failure Classifier (FC), where failures are assigned for every problematic operation in the process; 2) Failure Mode and Effect Analysis (FMEA), where every failure type weighted by Severity, Occurrence and Detection rating, calculated RPN value (in this research it will be named RPN_{Real}) and *PSPL* (Sahno *et al.*, 2013); 3) Failure Cost calculation (FCC), where the costs are calculated at the Bill of Material (BOM) level and financial impact of failure on final product. The applications of these tools/methods are described below.

Measure in FC. During the production process, an operation may have failure; therefore the Failure Cause/Group should be assigned to the problematic operation from the FC. This step is the basis for the next two steps in FMEA and FCC.

Measure in FMEA. One of the purposes of the FMEA is to assess the risks of the production processes that influence on product quality. Therefore, the purpose of the FMEA in this research is to monitor the product Quality KPI by reducing RPN_{Real} value of failures or eliminating them in the production process.

Usually the Severity, Occurrence and Detection ratings in FMEA are assessed in a team. In order to attain more precise results in FMEA that correspond to the data of real production, it is proposed in this research to assess the Occurrence rating based on production data from production floor. As for Severity and Detection ratings, they will be assessed in a team as usually using the FMEA rank tables. The techniques assessing these rating are described below.

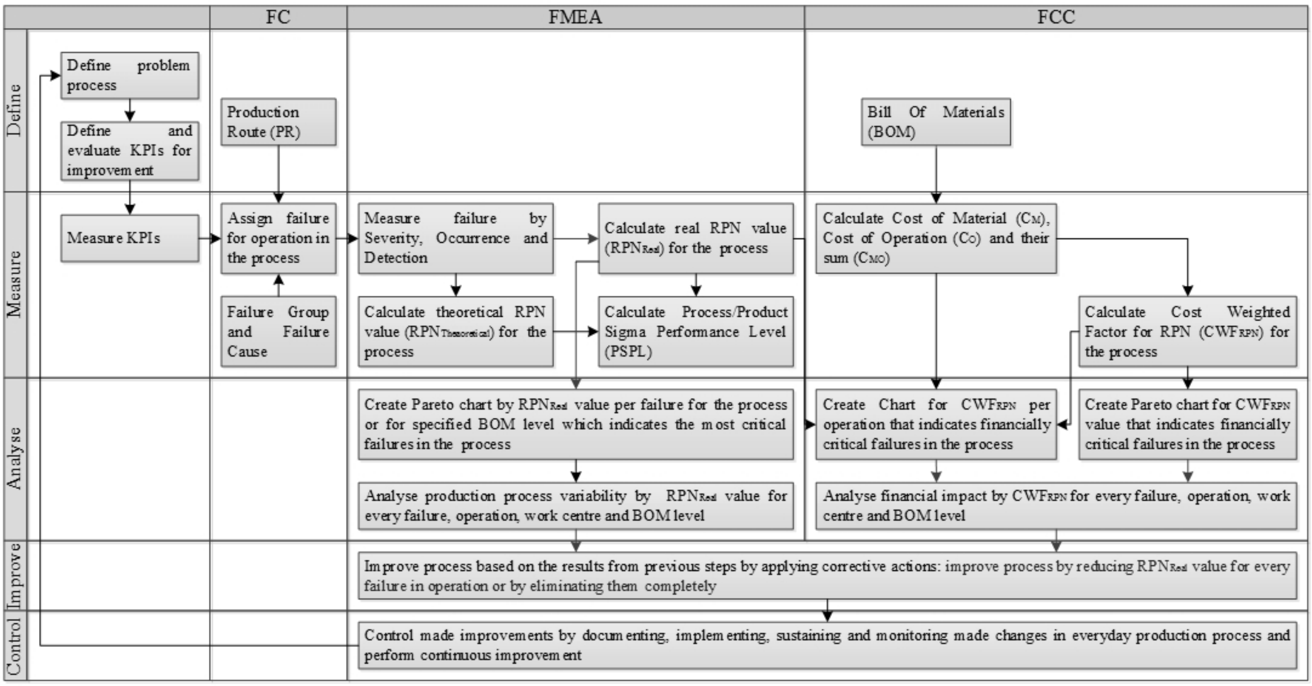


Figure 2. Framework for continuous improvement of production processes in Six Sigma DMAIC structure

Severity assessment: The goal of this rating is to assess how critical the effect of a potential failure mode is on the overall system or process. In some cases, it is clear from past experiences. In current research the rating of Severity is defined from the Severity ranks table and it is based on the knowledge and experience of the team members (MacDermott *et al.*, 1996).

Occurrence assessment: This rating is intended on assessment of failure frequency in production process. Occurrence is assessed according to the statistical data collected from production floor for the specified period of time (for instance, for one month). Below is presented Equation 4 that shows the way of calculation of Index of Occurrence (I_O).

$$I_O = \frac{\sum S_Q}{\sum P_Q} \times 100\% \qquad (4)$$

where:

ΣS_Q – scrap (non-qualified components/products) quantity occurred for the specified period;

ΣP_Q – produced product quantity for the specified period.

When the percent value for the Occurrence is calculated, it should be defined Occurrence rating from Occurrence ranks table (MacDermott *et al.*, 1996). For example, if there was checked 100 units and defined 10 scrap units, then the rating may equal to 10 points.

Detection assessment: The assessment of Detection is related to the performance of measurement tool that should check the required parameters in product and detect failures, before a product goes to a customer. In current research the rating of Detection is defined from the Detection ranks table and it is based on the knowledge and experience of the team members (MacDermott *et al.*, 1996).

RPN real (RPN_{Real}) value per failure calculation: By multiplying the three factors (S×O×D), the RPN_{Real} value is calculated for each failure.

RPN real (RPN_{Real}) value per operation, work centre, BOM level and process calculation: To calculate the sum of RPN_{Real} value per operation, work centre, BOM level and process, all RPN_{Real} values per failure should be summed up.

Theoretical RPN ($RPN_{Theoretical}$) value calculation: The maximum RPN_{Real} value for Severity, Occurrence and Detection rating may equal to 10 points, subsequently the maximum $RPN_{Theoretical}$ value for the failure can be 1000 points.

Theoretical RPN ($RPN_{Theoretical}$) per process calculation: To calculate the sum of $RPN_{Theoretical}$ value for the process/product, it should be counted the number of failures in the production process and multiplied by 1000 points. This $RPN_{Theoretical}$ value shows the scope of the process or the maximum RPN_{Real} value, which can be reached or to be failed.

RPN_{Real} percent calculation: To calculate the *PSPL* (which is described further), it should be calculated first RPN_{Real} percent value using the Equation 5.

$$RPN_{Real}\% = \frac{\sum RPN_{Real}}{\sum RPN_{Theoretical}} \times 100\% \qquad (5)$$

where:

ΣRPN_{Real} – sum of real RPN for a particular product,

$\Sigma RPN_{Theoretical}$ – sum of theoretical RPN for a particular product, ($S_{Max} \times O_{Max} \times D_{Max} = 10 \times 10 \times 10 = 1000$).

Process Yield (PY) calculation: Having calculated RPN_{Real} percent, now it can be calculated Process Yield (PY), using the Equation 6.

$$PY = 100\% - RPN_{Real}\% \qquad (6)$$

where:

100 % – maximum percent value of $\Sigma RPN_{Theoretical}$

Process/Product Sigma Performance Level (PSPL) calculation: The *PSPL* in this research shows the level of process/product quality that can be calculated using the RPN_{Real} per failure, operation, work centre, BOM level and common process, and $RPN_{Theoretical}$ values calculated in previous steps. Having calculated *PY* and according to the sigma performance scale in Table 1, the *PSPL* can be defined.

Measure in FCC. The purposes of the FCC approach in this research is to calculate Cost Weighted Factor for RPN (CWF_{RPN}) that shows failure financial impact (calculated in FMEA) on final product. In current research this factor should be reduced by improving or eliminating the RPN_{Real} values of failures in FMEA that influence on product Cost KPI. To calculate CWF_{RPN} for failure, operation and work centre it should be firstly calculated Cost of Material and Operation (C_{MO}) and to calculate CWF_{RPN} for BOM level, the Cost of BOM Level (C_{BOML}) should be calculated too.

Cost of Material and Operation (C_{MO}) calculation: To calculate C_{MO}, the Cost of Material (C_M) and Cost of Operation (C_O) should be summed. See Equation 7.

$$C_{MO} = C_M + C_O \qquad (7)$$

Cost of BOM Level (CBOML) calculation: In Figure 3, an example of product BOM structure is presented that consists of BOM levels and which contain other sub-levels and subsequent lower levels. The total cost of product equals to 100 % and this is the cost of BOM level zero – C_{BOML0}. The cost of C_{BOML0} equals to the sum of operation cost *($\sum C_{O0}$)* and sum of material cost *($\sum C_{M1}$)* from BOM level 1 *(C_{BOML1})*. Further, the cost of C_{BOML1} equals to the sum of operation cost *($\sum C_{O1}$)* and sum of material cost *($\sum C_{M2}$)* from BOM level 2 *(C_{BOML1})* and so forth until the lower level of a product. To calculate the C_{BOMLN}, it is proposed to use the Equation 8.

$$C_{BOMLN} = \sum_{y=1}^{m}\sum_{i=1}^{n} C_M yi + \sum C_O yi \qquad (8)$$

where:

C_{BOMLn} – cost of Bill Of Materials (BOM) of level n,

$y = 1 \div m$ – number of BOM levels;

$i = 1 \div n$ – number of components in BOM level;

C_{Mn} – material cost of BOM level n;

C_{On} – operation cost of BOM level n.

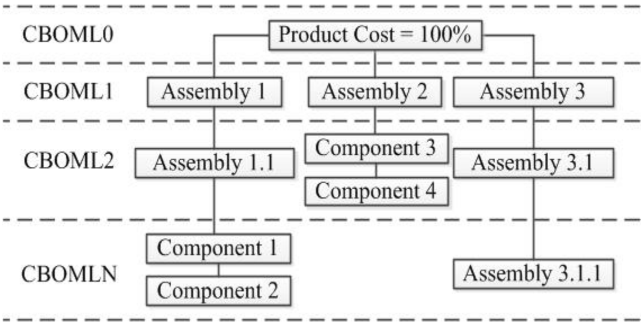


Figure 3. Product BOM structure with levels

Cost Weighted Factor of RPN (CWF_{RPN}) calculation: Based on the previous step, where C_{MO} and C_{BOMLN} was calculated, now, it should be calculated C_{WFRPN} per every failure, operation, work centre and BOM level that shows the financial impact on final product. To calculate CWF_{RPNFOW} per failure, operation, work centre the Equation 9 should be applied. To calculate $CWF_{RPNBOMLN}$ per BOM level, the Equation 10 should be applied.

$$CWF_{RPNFOW} = \frac{C_{MO}}{C_{BOML0}} \times \sum RPN_{Real} \qquad (9)$$

$$CWF_{RPNBOMLN} = \frac{C_{BOMLN}}{C_{BOML0}} \times \sum RPN_{Real} \qquad (10)$$

where:

CWF_{RPNFOW} – CWF of RPN per failure, operation and work centre,

$CWF_{RPNBOMLN}$ – CWF of RPN per BOM level N,

C_{MO} – Cost Of Material and Operation,

C_{BOMLn} – Cost of Bill Of Materials (BOM) of level n,

C_{BOML0} – upper BOM level that equals to 100% of product cost,

$\sum RPN_{Real}$ – sum of real RPN per failure, operation, work centre and BOM level.

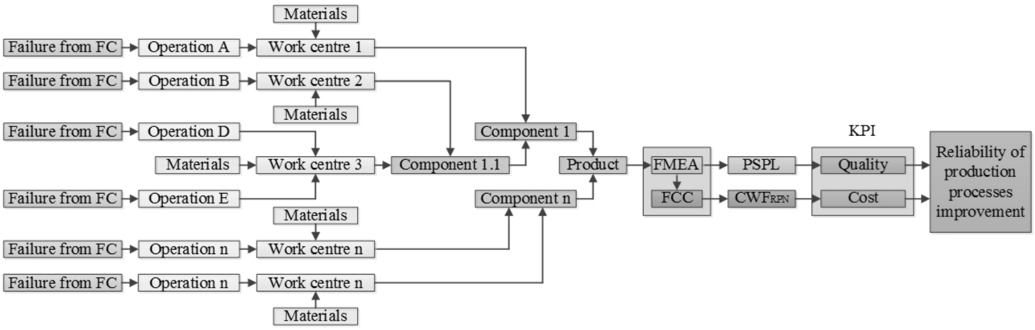


Figure 4. Production process structure for continuous improvement

Figure 4 shows the summary of Measure step where shown the new framework process that depicts the inputs of product production process and the failures that can occur. For example, a product contains components and sub-components and so on until the lower level. The components are processed in work centres, which have inputs – materials and operations. The operations have failures that assigned from FC and assessed by RPN_{Real}

values in FMEA. Further the *PSPL* in FMEA and CWF_{RPN} in FCC calculated that influence on Quality and Cost KPIs.

Analyse. The outcome of the Measure step enables to perform the analysis of production process/product and general production system in a different way for FMEA, and FCC phase, as described below.

Analyse in FMEA and FCC. Based on the received results in FMEA and FCC from Measure step, it should be built Chart for CWF_{RPN} and Pareto Chart and made their observation and comparison.

Chart for CWF_{RPN}, CMO and RPN_{Real} creation: This chart should be built for an operation using CWF_{RPN} and C_{MO} from FCC and RPN_{Real} value from FMEA. This chart visually should show which operations in the process/product have high RPN_{Real} value, C_{MO} and CWF_{RPN} comparing with other operations.

Pareto Chart creation: This chart should be built based on the calculated RPN_{Real} values from FMEA and CWF_{RPN} from FCC, which indicates the most critical failures in production process. Further, these charts can be compared as follows:

It indicates that the failures of these charts are located in different sequence. The Pareto chart based on RPN_{Real} from FMEA shows failure sequence that are influence on Quality KPI. The Pareto chart based on CWF_{RPN} from FCC shows failure sequence that influence on Cost KPI. Comparing these charts, an engineer can make decision on which KPI is more important for some specified product type or for general production system or for some customer.

Analyse in FMEA. Using RPN_{Real} values from FMEA, it can be observed the process variability of work centres, operations and failures in the following way:

Work Centre: It should be selected specific work centre, which shows what operations and failures it has, it shows an average RPN_{Real} value for specific work centre and in what BOM level and product type it used.

Operation: A specific operation should be selected, that can show what failure types this operation has and in what work centre, BOM level and product type it is used. In addition, it can be selected for example, some specific operation in the process and calculated an average RPN_{Real} value, or selected all existing operations and defined most problematic operation with high RPN_{Real} value.

Failure Group and/or Failure Cause: Failure Causes (sub-groups) should be grouped according to their main Failure Group. Further, it can be possible to see the specific failure variability by RPN_{Real} value it has. In addition, it can be observed in what operation, work centre, BOM level of the product that specific failure exists. In addition, an average RPN_{Real} value of the failure for the process can be calculated.

Analyse in FCC. The analysis in FCC should be explained using the following example. A BOM level has 10% of cost of final product and it has high RPN_{Real} values and at the same time there is another BOM level, which has 20% of cost of final product and it has same RPN_{Real} values or may be even lower, then, there should be made a decision for BOM level that has higher cost. In other words, the CWF_{RPN} indicates the cost weight of failures, operations and BOM levels of final product. This kind of cost weighted factor assessment allows engineers to pay attention on more important problems, which have financial impact on final product. This approach allows decreasing the number of scrap, as a result it enables to save money and increase company revenue.

The above presented example may have exceptions. For instance, if a cost of some BOM level is 10 % of final product cost and it has high RPN_{Real} values, but it does not influence on entire product quality, e.g. a scrap component can be replaced or demounted from design point of view, then, in this case, the financial impact will be low. Another example, if a cost of BOM level is 10 % of final product cost and it has low RPN_{Real} values, but it can influence on entire product quality e.g. the scrap component cannot be replaced or demounted from the final product, as a result, an entire product may go to scrap, so the financial impact will be high. In this case, improvements should be made for BOM level, which has high financial impact on product.

Improve. Perform corrective actions based on the results from previous steps (measure, analyse): generate various potential solutions and select the best one, assess the effect of the solution (identify what KPI is more important for the particular product or for general production system or for customer) and implement the solution (reduce the RPN_{Real} value for the harmful failure in operation or eliminate them completely). The more reliable production process, the less process variability, the less number of defects, failures or RPN_{Real} values in the process, therefore, less product scrap and higher product Quality KPI. Subsequently, less product financial losses that in turn the higher Cost KPI. In case the improvement requires financial investment, it is necessary to calculate how soon the investment starts to pay off for itself (when the break-even point starts) (Badiru, 2005).

When the corrective actions applied, an engineer should follow them by performing “mini DMAIC” process, as follows:

Define the object of study that is something that has been corrected or improved.

Measure the improved process by assigning failures from FC and assessing RPN_{Real} in FMEA.

Analyse processes and decide where and what corrective actions are necessary to carry out.

Improve process (if needed).

Control made improvements in daily processes, if the process requires to repeat an improvement, then repeat the "mini DMAIC" process again until the changes are satisfy.

Control. Ensure that the implemented solution is working by applying "mini DMAIC" process. If proposed changes are satisfying and not require any more corrective actions, then proceed to the improvements with other processes. Document, apply, sustain and monitor made improvements in real processes of everyday production.

This framework enables to decrease the number of defects/failures in the process, thus decreasing their RPN_{Real} value that in turn increases such indicators as Process/Product Sigma Performance Level (PSPL) and Cost Weighted Factor of RPN (CWF_{RPN}) that influences on KPIs as product, Quality and Cost that in turn influences on customer satisfaction and company revenue.

Computational Experiment

In this research a computational experiment of the new framework for continuous improvement of production processes is checked with the production process related data. The computational experiment was made on a "Wind Power Generator A" product that is used in windmills for generation of energy. This product - assembly consists of some sub-assemblies that is presented in Figure 5 in the form of BOM structure.

Define. One of the main tasks of computational experiment in DMAIC is to identify problematic process and the main KPIs that should be continuously improved.

Process: The problematic process is displayed in the form of PR card with "Wind Power Generator A" product. The PR consists of two parts (see Figure 6): Product Data which contains product name to be produced, BOM levels of product, component ID and name, and quantity to be produced; Production Data which contains work centre name, where component to be processed, operations name, its sequence and operation time.

KPI: Today, to find out what KPIs are important for the customer, companies use survey techniques and questionnaires that enable to define them. In most cases, companies and customers calculate KPI metrics using its own calculations, for example based on received reclamations from production floor or customer. Taking into account the considerable complexity of the manufacturing sector, this research focused on two KPIs – product Quality and Cost.

Quality metric is a calculation of the amount of quality delivered units versus the amount of non-quality units. For instance: Company received 10 units. The order has 2 defect units. The Quality metric for this order is 80 %. Calculation: Number of quality units received / Total number of ordered units (8/10 = 80 %).

Cost metric is very important for any company that wants to increase their revenue, therefore the goal in this research is to increase company revenue by means of improving production processes reliability and Quality that in turn directly influence on Cost KPI.

The main KPI metrics have been identified and evaluated. Further it is presented new framework application with production related data that explains how process indicators which influence on KPIs can be calculated and improved.

Measure. In Measure step different tools/methods (FC, FMEA and FCC) are discussed.

Measure in FC. It is defined Failure Cause and Failure Group in FC for each operation during the production process (see Figure 6).

Measure in FMEA. In FMEA every failure assessed by Severity, Occurrence and Detection rating, which gives the RPN_{Real} value. This value calculated for every failure, operation, BOM level and process or product.

Severity assessment: Severity rating is defined according to the Severity scale that indicates the effect of a failure; it is based on the knowledge and experience of the team members (MacDermott, 1996).

Occurrence assessment: This rating intended on assessment of failure frequency in production process and in this computational experiment applied the following example; the production line passed 500 units of a component during one month on operation "OpA" in work centre "W1". From 500 units, there is 1 unit that has failure cause occurred – "7C. Defective material" that is in failure group – "7. Supplier problem". To define Occurrence rating, the Index of Occurrence (I_O) should be calculated firstly using Equation 4 that shows that there are 0,2 % of failures each month. Then using this index, the Occurrence rating can be defined using the Occurrence rating table (MacDermott *et al.*, 1996) which shows that 1 scrap in 500 units equals to 6 points of Occurrence rating – moderate.

$$I_O = \frac{1}{500} \times 100\% = 0{,}2\%$$

Detection assessment: The purpose of this rating is to detect the failure before it happens on customer side. Before start failure detection, it should be beforehand specified parameters of the product that should be checked. The specified parameters of these units should be checked according to the customer needs. Before testing an item, it should be beforehand defined parameters, which customer needs to be tested, and if there are flaws, they should be defined and eliminated. If the failure was defined in further production stages or by customer on his side, the Detection value will increase (MacDermott, 1996).

RPN real (RPN_{Real}) value per failure calculation: By multiplying the three factors (S×O×D), the RPN_{Real} value is calculated for each failure (Figure 6).

RPN real (RPN_{Real}) value per operation, work centre, BOM level and process calculation: The sum of RPN_{Real} value was calculated by summing up all RPN_{Real} values per failure. For example 164 points per operation "OpB"; 272 points per work centre "W1"; 608 points per BOM level "1"; 2000 points per process (Figure 6).

Theoretical RPN ($RPN_{Theoretical}$) per process calculation: To calculate the $RPN_{Theoretical}$ per process it should be counted the number of failures occurred in the process and multiplied by $RPN_{Theoretical}$ per failure (1000 points). Figure 6 shows the process of three assemblies or BOM level - "1" (Balanced Rotor, Connected Stator and Frame) and Assembled Generator or BOM level - "0" – which are processed in work centres. These work centres have 12 operations with 20 failures occurred. As the $RPN_{Theoretical}$ value for every failure is 1000 points (10x10x10) and there found 20 failures in the process, the sum of $RPN_{Theoretical}$ value per process for the "Wind Power Generator A" equals to 20000 points (20x1000). This value used to define the scope of the common production process that equals to 100 %.

RPN_{Real} percent calculation: After calculating the sum of RPN_{Real} (2000 points) and $RPN_{Theoretical}$ (20000 points) value for the process or product, now these values can be used to calculate RPN_{Real} percent per process using the Equation 5.

$$RPN_{Real}\% = \frac{2000}{20000} \times 100\% = 10\%$$

Process Yield (PY) calculation: According to the above calculations, the RPN_{Real} per process equals to 2000 points that makes 10 % from $RPN_{Theoretical}$ value of 20000 points. As the RPN_{Real} equals to 10%, then the PY can be calculated using the Equation 6, extracting the RPN_{Real} per cent (10 %) from the $RPN_{Theoretical}$ per cent (100,%).

$PY = 100\,\% - 10\,\% = 90\,\%$

Process/Product Sigma Performance Level (PSPL) calculation: As the *PY* equals to 90% that shows, according to the sigma performance scale in Table 1, the *PSPL* for the current process or product equals to 2,78 δ.

If the company produces 5 products and every product has its own *PSPL*, an average *PSPL* for all products can be calculated in the following way: the calculated *PSPLs* should be summed up and divided into 5 products. As the result, the average *PSPL* is 2,8 δ.

$PSPL_{Average} = 2{,}78 + 2{,}9 + 2{,}7 + 3 + 2{,}6 \approx 2{,}8\,\delta$

Measure in FCC. The FCC phase in this research divided into two parts: in the first part calculated C_{MO} and C_{BOML} that is the basis for the CWF_{RPN} calculation.

Cost of Material and Operation (C_{MO}) calculation: To calculate C_{MO}, the C_M (25 %) and C_O (1 %) should be summed (Figure 6) using Equation 7. It shows that the cost of material of "Balanced Rotor" and operation "OpA" equals to 26 %. Further, this value used to calculate CWF_{RPN} per failure, operation and work centre.

$C_{MO} = 25 + 1 = 26\,\%$

Cost of BOM Level (C_{BOML}) calculation: In Figure 5 presented an example of product BOM structure. From the right side of each component, assembly and final product defined value-added operation cost (C_O) (in per cent value). For instance, the C_O of Assembled Generator is 10% from the final product cost, it means the assembled together Connected Stator, Frame and Balanced Rotor costs to 10% of final product. From the left side defined the value-added material cost (C_M) (in per cent value), which includes the cost of BOM of lower level ($C_{BOMLN-1}$), because the lower level BOM is the material/component (that already has cost) for the upper BOM level. The Equation 8 and values from Figure 5 is used to calculate the cost of C_{BOML1} (Connected Stator) and C_{BOML0} (Assembled Generator).

Cost Weighted Factor for RPN (CWF_{RPN}) calculation: To calculate the financial impact of failure, operation and work centre on final product the Equation 9 should be used. Below is presented the example for failure cause - 7.C Defective Material; operation - OpA; and work centre - W2.

Failure Cause: 7.C Defective Material

$$CWF_{RPNFOW} = \frac{26}{100} \times 108 = 28.1$$

Operation: OpA

$$CWF_{RPNFOW} = \frac{26}{100} \times (80 + 84) = 42.6$$

Work Centre: W2

$$CWF_{RPNFOW} = \frac{28}{100} \times (120 + 120 + 96) = 94.1$$

Same approach should be applied for every failure, operation and work centre in the process.

The similar approach should be applied for every BOM level in the process using the Equation 10.

BOML1: Balanced Rotor

$$CWF_{RPNBOML} = \frac{30}{100} \times (108 + 80 + 84 + 120 + 96) = 182.4$$

BOML1: Connected Stator

$$CWF_{RPNBOML} = \frac{50}{100} \times (105 + 72 + 96 + 90 + 128) = 245.5$$

CBOML1: Cost of Connected Stator = Connected Stator (C_{O1}) + Impregnated Stator (C_{BOML2})

$C_{BOML1} = \Sigma C_{O1} + \Sigma C_{BOML2}$

$C_{BOML1} = 5\% + 45\% = 50\%$

CBOML0: Cost of Assembled Generator = Assembled Generator (C_{O0}) + (Connected Stator (C_{BOML1}) + Frame (C_{BOML1}) + Balanced Rotor (C_{BOML1}))

$C_{BOML0} = \Sigma C_{O0} + \Sigma C_{BOML1}$

$C_{BOML0} = 10\% + (50\% + 10\% + 30\%) = 100\%$

Same approach should be applied for remained BOM levels and components until the lower level of the product.

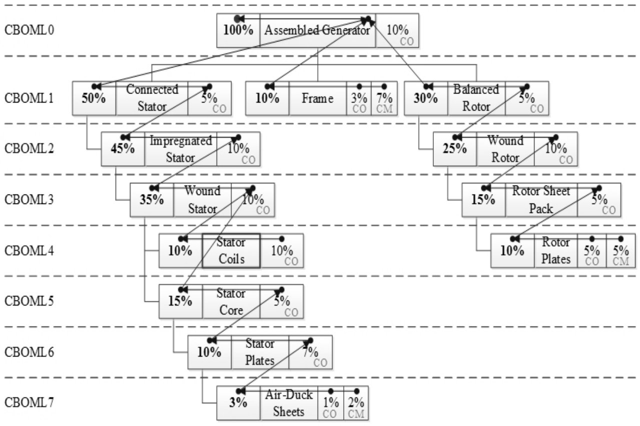
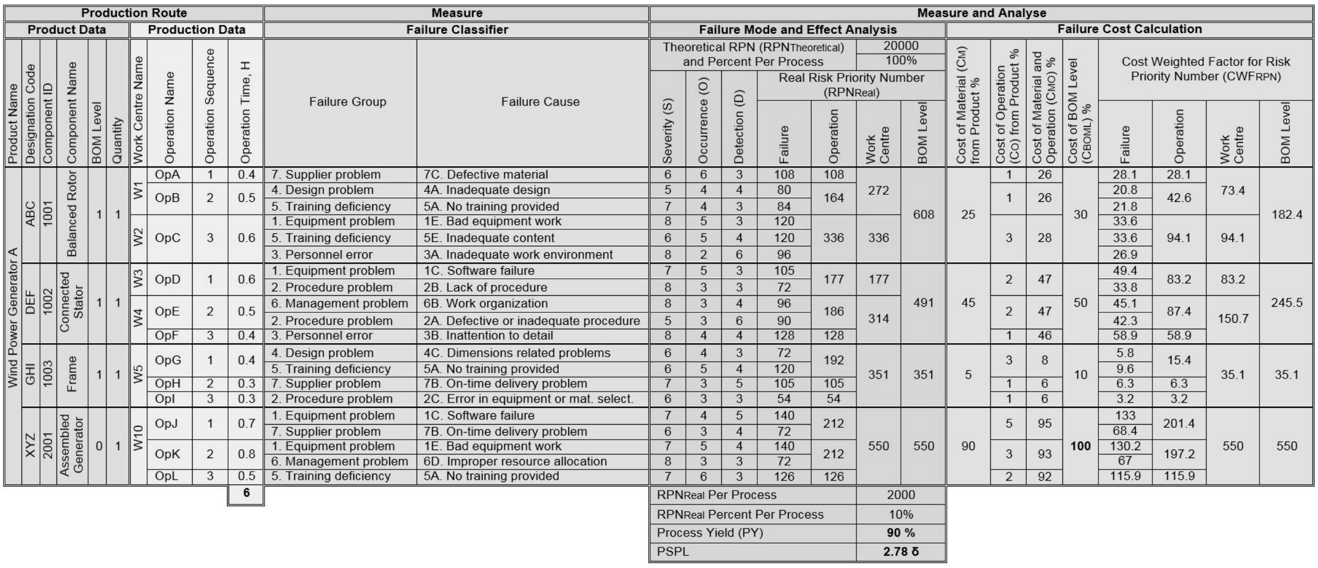


Figure 5. Assembled Generator BOM structure

Analyse. The results from the Measure step enable to create various charts and diagrams, and perform the analysis of the data from FMEA and FCC phases.

Analyse in FMEA and FCC. Based on the calculated data in FMEA and FCC, from the Measure step, it is created various charts that allow analyse these results. The Cost Weighted Chart for CWF_{RPN} and Pareto charts are built and their comparison made.

Chart for CWF_{RPN}, C_{MO} and RPN_{Real} creation: Figure 7 presents Cost Weighted Chart for RPN_{Real} per operation from FMEA, for CWF_{RPN} and C_M and C_O from FCC. This chart visually shows which operations have high RPN_{Real} value (quality), CWF_{RPN} and C_{MO} (cost) impact on final product (for example these are operations "OpJ" and "OpK"). The chart shows that these operations are critical from all point of views (quality and cost) and they have priority for improvement comparing with others, for example, visually it can be noticed that operation "OpI" has low RPN_{Real} value, material/component cost and low CWF_{RPN}. Other words it does not have high impact on quality and cost impact on final product.



Production Route										Measure		Measure and Analyse														
Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis							Failure Cost Calculation							
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Theoretical RPN ($RPN_{Theoretical}$) and Percent Per Process					20000 100%		Cost of Material (C_M) from Product %	Cost of Operation (C_O) from Product %	Cost of Material and Operation (C_{MO}) %	Cost of BOM Level (C_{BOML}) %	Cost Weighted Factor for Risk Priority Number (CWF_{RPN})			
												Severity (S)	Occurrence (O)	Detection (D)	Real Risk Priority Number (RPN_{Real})											
															Failure	Operation	Work Centre	BOM Level					Failure	Operation	Work Centre	BOM Level
Wind Power Generator A	ABC	1001	Balanced Rotor	1	1	W1	OpA	1	0.4	7. Supplier problem	7C. Defective material	6	6	3	108	108	272	608	25	1	26	30	28.1	28.1	73.4	182.4
							OpB	2	0.5	4. Design problem	4A. Inadequate design	5	4	4	80	164				1	26		20.8	42.6		
										5. Training deficiency	5A. No training provided	7	4	3	84								21.8			
						W2	OpC	3	0.6	1. Equipment problem	1E. Bad equipment work	8	5	3	120	336	336			3	28		33.6	94.1	94.1	
										5. Training deficiency	5E. Inadequate content	6	5	4	120								33.6			
										3. Personnel error	3A. Inadequate work environment	8	2	6	96								26.9			
	DEF	1002	Connected Stator	1	1	W3	OpD	1	0.6	1. Equipment problem	1C. Software failure	7	5	3	105	177	177	491	45	2	47	50	49.4	83.2	83.2	245.5
										2. Procedure problem	2B. Lack of procedure	8	3	3	72								33.8			
						W4	OpE	2	0.5	6. Management problem	6B. Work organization	8	3	4	96	186	314			2	47		45.1	87.4	150.7	
										2. Procedure problem	2A. Defective or inadequate procedure	5	3	6	90								42.3			
							OpF	3	0.4	3. Personnel error	3B. Inattention to detail	8	4	4	128	128				1	46		58.9	58.9		
	GHI	1003	Frame	1	1	W5	OpG	1	0.4	4. Design problem	4C. Dimensions related problems	6	4	3	72	192	351	351	5	3	8	10	5.8	15.4	35.1	35.1
										5. Training deficiency	5A. No training provided	6	5	4	120								9.6			
							OpH	2	0.3	7. Supplier problem	7B. On-time delivery problem	7	3	5	105	105				1	6		6.3	6.3		
							OpI	3	0.3	2. Procedure problem	2C. Error in equipment or mat. select.	6	3	3	54	54				1	6		3.2	3.2		
	XYZ	2001	Assembled Generator	0	1	W10	OpJ	1	0.7	1. Equipment problem	1C. Software failure	7	4	5	140	212	550	550	90	5	95	**100**	133	201.4	550	550
										7. Supplier problem	7B. On-time delivery problem	6	3	4	72								68.4			
							OpK	2	0.8	1. Equipment problem	1E. Bad equipment work	7	5	4	140	212				3	93		130.2	197.2		
										6. Management problem	6D. Improper resource allocation	8	3	3	72								67			
							OpL	3	0.5	5. Training deficiency	5A. No training provided	7	6	3	126	126				2	92		115.9	115.9		
									6			RPN_{Real} Per Process					2000									
												RPN_{Real} Percent Per Process					10%									
												Process Yield (PY)					**90 %**									
												PSPL					**2.78 δ**									

Figure 6. Integrated report of PR card, FC, FMEA and FCC

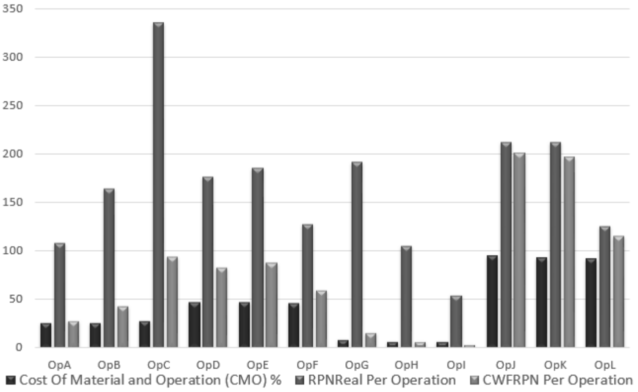


Figure 7. Chart for *RPN_{Real}*, *C_{MO}* and *CWF_{RPN}* per operation

Pareto chart creation for RPN_{Real}: Based on the calculated *RPN_{Real}* values from FMEA (Figure 6), it is created Pareto chart per failure that also shows in what operation it happened. The chart presented in Figure 8 indicates the most critical failures in production process from product quality point of view. Using this chart, an engineer can define what failures should be eliminated or at least where *RPN_{Real}* values should be decreased in order to improve *PSPL* that influence on Quality KPI.

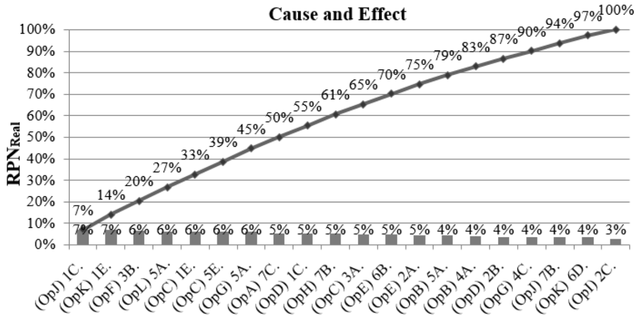


Figure 8. Pareto chart for *RPN_{Real}* of failure per operation

Pareto chart creation for CWF_{RPN}: Based on the calculated *CWF_{RPN}* values from FCC (Figure 6), it is created Pareto chart for per failure that also shows in what operation it happened (similar as for *RPN_{Real}* presented in Figure 8). The chart presented in Figure 9 indicates the most critical failures in the process from financial point of view. Using this chart, an engineer can define what failures should be decreased or eliminated to improve product *CWF_{RPN}* that influence on Cost KPI.

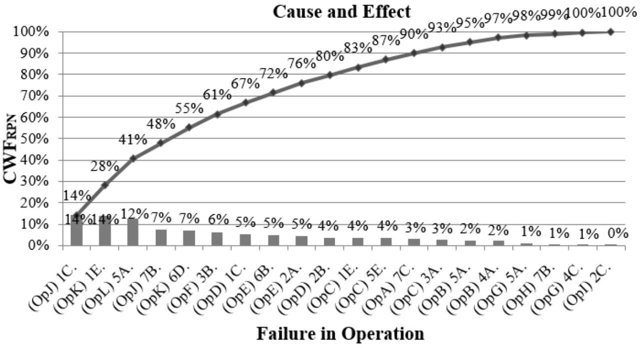
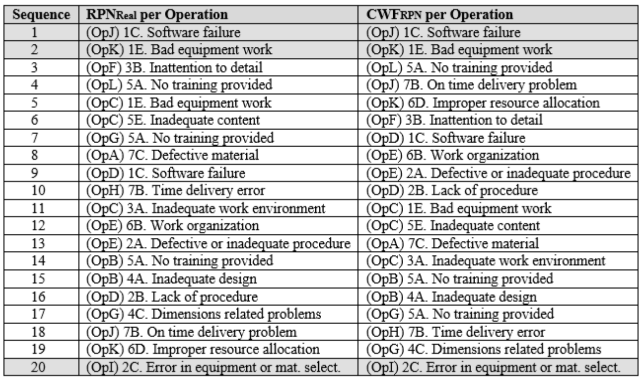


Figure 9. Pareto chart for *CWF_{RPN}* of failure per operation

Comparing these two charts, it shows that the failures have different sequence. For example, the sequence of failures in Pareto chart for *RPN_{Real}* in FMEA is different from the sequence of failures in Pareto chart for *CWF_{RPN}* in FCC. Figure 10 presents failure sequence difference which shows that the sequence of only three failures/operations was not changed (1, 2, 20), all other failures are in different sequence. It is operations ("OpJ", "OpK" and "OpI") that has been already mentioned in Figure 7. It shows that operations "OpJ" and "OpK" are very critical from all quality and cost point of view and the operation "OpI" has low importance. Comparing these results, an engineer, for instance, can make decision that it is more essential for the current process to improve first two operations that influence on *PSPL* and *CWF_{RPN}* indicators and subsequently on Quality and Cost KPIs.



Sequence	RPN_{Real} per Operation	CWF_{RPN} per Operation
1	(OpJ) 1C. Software failure	(OpJ) 1C. Software failure
2	(OpK) 1E. Bad equipment work	(OpK) 1E. Bad equipment work
3	(OpF) 3B. Inattention to detail	(OpL) 5A. No training provided
4	(OpL) 5A. No training provided	(OpJ) 7B. On time delivery problem
5	(OpC) 1E. Bad equipment work	(OpK) 6D. Improper resource allocation
6	(OpC) 5E. Inadequate content	(OpF) 3B. Inattention to detail
7	(OpG) 5A. No training provided	(OpD) 1C. Software failure
8	(OpA) 7C. Defective material	(OpE) 6B. Work organization
9	(OpD) 1C. Software failure	(OpE) 2A. Defective or inadequate procedure
10	(OpH) 7B. Time delivery error	(OpD) 2B. Lack of procedure
11	(OpC) 3A. Inadequate work environment	(OpC) 1E. Bad equipment work
12	(OpE) 6B. Work organization	(OpC) 5E. Inadequate content
13	(OpE) 2A. Defective or inadequate procedure	(OpA) 7C. Defective material
14	(OpB) 5A. No training provided	(OpC) 3A. Inadequate work environment
15	(OpB) 4A. Inadequate design	(OpB) 5A. No training provided
16	(OpD) 2B. Lack of procedure	(OpB) 4A. Inadequate design
17	(OpG) 4C. Dimensions related problems	(OpG) 5A. No training provided
18	(OpJ) 7B. On time delivery problem	(OpH) 7B. Time delivery error
19	(OpK) 6D. Improper resource allocation	(OpG) 4C. Dimensions related problems
20	(OpI) 2C. Error in equipment or mat. select.	(OpI) 2C. Error in equipment or mat. select.

Figure 10. Summary of failure sequence from Pareto charts

Analyse in FMEA. By applying the RPN_{Real} values from FMEA it can be observed the process variability of work centres, operations and failures, identified minimum and maximum RPN_{Real} value per failure, in addition it can be calculated an average RPN_{Real} value per general production process. Every production process may consist of many different operations, which operate in a specified order; moreover, these operations can be reused in same production process. In addition, some specified operation may have different or even same failure cause and same or different RPN_{Real} value in same production process and/or in general production system. Other words, the variability may be huge. This kind of process analysis allows better understand what work centres, operations and failures are critical for the general production system. Engineer can identify the most harmful failures with high RPN_{Real} value and improve or eliminate it. Similar analysis can be done not only for general production system, but also for some specified product type.

Analyse in FCC. After calculating CWF_{RPN} for both BOM levels (Connected Stator and Balanced Rotor) in Measure step, it can be done the following summary using the data from Figure 6. The CWF_{RPN} value for Connected Stator is higher than CWF_{RPN} value for Balanced Rotor, despite of the fact that the Balanced Rotor has more failures and higher RPN_{Real} value per BOM level in FMEA than Connected Stator. It means that the improvements should be done on Connected Stator that has high financial impact on final product.

Improve. Based on the results from the first two steps, an engineer can develop improvement program that enables to decrease production process variability, number of defects or failures and improve production processes reliability. Below is presented example of corrective actions for every KPI.

In order to improve Quality KPI, it is first necessary to determine on what *PSPL* process operates and which failures are most harmful to the production process (using RPN_{Real} values), i.e. determine what failures have a negative impact on the quality of the semi-products as well as on the final product. The Figure 8 shows that the most harmful failures (according to the Pareto law 80/20) are: "(OpJ) 1C. Software failure", "(OpK) 1E. Bad equipment work" and "(OpF) 3B. Inattention to detail". These failures related to the "Equipment problem" and "Personnel error" failure group. From here can be made summary, in order to reduce the RPN_{Real} values of these failures or eliminate them completely and increase *PSPL* that influence on Quality KPI, it is necessary to take corrective actions. For example, provide to employee required training how to operate machine, create simple and clear instruction guide and during the training period provide more experienced operator as the mentor who can help acquire needed experience.

The same approach should be carried out for the Cost KPI. It is necessary to determine which failures are most harmful from the financial point of view in the production process (using CWF_{RPN} values). Figure 9 shows that the most harmful failures are: "(OpJ) 1C. Software failure", "(OpK) 1E. Bad equipment work" and "(OpL) 5A. No training provided". These failures related to the "Equipment problem" and "Training deficiency" failure group. As in the previous case, in order to improve Cost KPI, it is necessary firstly reduce the RPN_{Real} values of the failures or eliminate them completely that influence on high CWF_{RPN} values. In that case, as in previous example, there should be provided to employee required training how to operate machine, create simple and clear instruction guide and during the training period provide more experienced operator as the mentor who can help acquire needed experience.

From the two examples above, it can be done the following summary that the cause of poor product quality and financial losses is the lack of operator knowledge and experience. In that case, in order to increase these KPIs, company management should provide to the operators required trainings that increase their competence.

Control. The purpose of the Control step is to document and sustain made improvements and monitor implemented solution in daily production process. Check made improvements and apply "mini DMAIC" process if needed. Perform continuous improvements for the improved process. If the implemented corrective actions satisfy, then continuous improvement for other problem processes should be proceeding.

Conclusion

In this paper a new framework was demonstrated for continuous improvement of production processes using rigorous Six Sigma DMAIC methodology. In the Define step, the problem and main KPIs for improvement are identified. In the Measure step, the modified Failure Classifier (FC) standard, i.e. DOE-NE-STD-1004-92 was applied, which enabled to specify the types of failures for each operation during the production process. In addition, the Failure Mode and Effect Analysis (FMEA) is applied to assess the weight of the each failure by Severity, Occurrence and Detection rating and then calculated the RPN_{Real} value. Based on the FMEA results, the *PSPL* was calculated that indicated the general level of quality for the process/product that influence on Quality KPI. Using the RPN_{Real} values from FMEA the variability of the process by failures, operations work centres and BOM level was observed. In addition, the costs of the components and/or BOM level was calculated in FCC, in order to further define the financial impact of failure *(*CWF_{RPN}*)* on final product. This factor showed where should be made improvements to increase Cost KPI.

This framework enables an engineer to perform daily monitoring of production processes (based on data for the previous day); determine what failure is the most harmful in the process from product quality and cost and point of view; perform continuous improvement of production processes and their indicators that affect the KPIs, this in turn helps to improve customer satisfaction and financial performance of the company.

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References

Anbari, F. T. (2002). Six sigma method and its applications in project management. In Proceedings of the Project Management Institute Annual Seminars and Symposium [CD], San Antonio, Texas. Oct (Vol. 3, No. 10). http://dx.doi.org/10.1108/13683040210451679

Antony, J., & Banuelas, R. (2002). Key ingredients for the effective implementation of Six Sigma program. *Measuring Business Excellence*, 6(4), 20–27.

Aon Management Consulting. (2003). Lean Six Sigma. Leadership Report.

Badiru, A. B. (2005). Handbook of industrial and systems engineering, CRC Press. http://dx.doi.org/10.1201/9781420038347

Barchetti, U., Bucciero, A., Guido, A. L., Mainetti, L., & Patrono, L. (2011). Supply Chain Management and Automatic Identification Management convergence: Experiences in the Pharmaceutical Scenario. Supply Chain Coordination and Management. Vienna: IN-TECH Education and Publishing.

Bhanumurthy, M. V. (2012). Profitability through lean Six Sigma: Save energy - Save environment. AIChE Annual Meeting, Conference Proceedings.

Brook, Q. (2010). Lean Six Sigma and Minitab. The Complete Toolbox Guide For All Lean Six Sigma Practitioners.

Chiarini, A. (2012). Risk management and cost reduction of cancer drugs using Lean Six Sigma tools. *Leadership in Health Services*, 25(4), 318–330. http://dx.doi.org/10.1108/17511871211268982

Desai, T. N., & Shrivastava, R. L. (2008, October). Six Sigma–a new direction to quality and productivity management. In Proceedings of the World Congress on Engineering and Computer Science, San Francisco, CA. Elsevier.

DOE-NE-STD-1004-92. (1992). Root Cause Analysis Guidance Document, US http://www.everyspec.com/DOE/DOE+PUBS/DOE_NE_STD_1004_92_262 (11.2012).

Hennig-Thurau, T., & Klee, A. (1997). The impact of customer satisfaction and relationship quality on customer retention: A critical reassessment and model development. *Psychology & Marketing*, 14(8), 737–764. http://dx.doi.org/10.1002/(SICI)1520-6793(199712)14:8<737::AID-MAR2>3.0.CO;2-F

Johnson, S. K. (1998). Combining QFD and FMEA to optimize performance. *In Annual Quality Congress Proceedings-American Society For Quality Control*, 564–575.

Karaulova, T., Kostina, M., & Sahno, J. (2012). Framework of reliability estimation for manufacturing processes. *Mechanics*, 18(6), 713–720.

Kostina, M., Karaulova, T., Sahno, J., & Maleki, M. (2012). Reliability estimation for manufacturing processes. *Journal of Achievements in Materials and Manufacturing Engineering*, 51(1), 7–13.

Krishna, R., & Dangayach, G. S. (2007). Six Sigma implementation at an auto component manufacturing plant: a case study. *International Journal of Six Sigma and Competitive Advantage*. 3(3), 282–302. http://dx.doi.org/10.1504/IJSSCA.2007.015070

Kwak, Y. H., & Anbari, F. T. (2006). Benefits, obstacles, and future of six sigma approach. *Technovation*, 26(5), 708–715. http://dx.doi.org/10.1016/j.technovation.2004.10.003

MacDermott, R. E., Mikulak, R. J., & Beauregard, M. R. (1996). The basics of FMEA. Productivity Press.

McClusky, R. (2000). Six Sigma Special The rise, fall and revival of six sigma. Measuring Business Excellence, 4(2), 6–17.

Mekki, K. S. (2006). Robust design failure mode and effects analysis in designing for Six Sigma. *International Journal of Product Development*, 3(3), 292–304. http://dx.doi.org/10.1504/IJPD.2006.009895

Production Route Card, Available from: http://www.enotes.com/american-scholar/q-and-a/what-meant-by-job-card-route-card-used-production-99397, Accessed: 09.2013.

Rancour, T. and McCracken, M. (2000). Applying six sigma methods for breakthrough safety performance. *American Society of Safety Engineers*, 31–4.

Sahno, J., Opik, R., Kostina, M., Paavel, M., Shevtshenko, E., & Wang, Y. (2012). Knowledge Management Framework for Production Route Selection in Manufacturing Enterprises. *In 8th International DAAAM Baltic Conference Industrial Engineering*, 567–572.

Sahno, J., Sevtsenko, E., & Karaulova, T. (2013). Knowledge Management Framework for Six Sigma Performance Level Assessment. In Advances in Information Systems and Technologies. *Springer Berlin Heidelberg*, 255–267. http://dx.doi.org/10.1007/978-3-642-36981-0_25

Sahno, J., & Shevtshenko, E. (2014). Quality Improvement Methodologies for Continuous Improvement of Production Processes and Product Quality and Their Evolution. *9th International DAAAM Baltic Conference Industrial Engineering*, 181–186.

Sarkar, B. N. (2007). Designing sustainable strategies for continuous improvement deployment programme: lessons from a steel plant in India. *International Journal of Six Sigma and Competitive Advantage*, 3(4), 352–376. http://dx.doi.org/10.1504/IJSSCA.2007.017177

Seemer, R.H. (2010). Defects Per Million Opportunities (DPMO).

Six Sigma, Available from: http://www.isixsigma.com/new-to-six-sigma/sigma-level/how-calculate-process-sigma, Accessed: 01.2015.

Stamatis, D. H. (2003). Failure mode and effect analysis: FMEA from theory to execution. Asq Press.

Stephens, J. S., & McDonald Jr, C. L. (2007). Lean Six Sigma. *The Journal of Organizational Leadership and business*. Retrieved November, 24, 2010.

Umble, E. J., Haft, R. R., & Umble, M. M. (2003). Enterprise resource planning: Implementation procedures and critical success factors. *European journal of operational research*, 146(2), 241–257. http://dx.doi.org/10.1016/S0377-2217(02)00547-7

Van Den Heuvel, Does, R. J., & De Koning, H. (2006). Lean Six Sigma in a hospital. *International Journal of Six Sigma and Competitive Advantage*, 2(4), 377–388. http://dx.doi.org/10.1504/IJSSCA.2006.011566

Watson G. H. (2004). Six Sigma for Business Leaders, First Edition, Business Systems Solutions, Inc. USA.

Weber, A., & Thomas, I. R. (2005). Key performance indicators. Measuring and Managing the Maintenance Function, Ivara Corporation, Burlington.

Womack, J. P., Jones, D. T., & Roos, D. (1990). The Machine that Changed the World: The Story of Lean Production HarperCollins Publishers, New York, USA.

Womack, J., & Jones, D. (1994). From lean production to the lean enterprise. Harvard Business Review, 72(2), 93–103.

Yang, M. S., Li, Y., Liu, Y., & Gao, X. Q. (2010). A Method for Problem Selection in the 6σ Definition Stage, Advanced Materials Research, 139, 1485–1489. http://dx.doi.org/10.4028/www.scientific.net/AMR.139-141.1485

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