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Approach for the Evaluation of Preventive Quality Activities Based on the Combined Reduction of Potential Failure Costs and CO_2-Emissions

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Abstract: The decoupling of growth and resource consumption is a central challenge for the production industry. Especially under the current circumstances, it is important to use the available resources optimally and not to waste anything. Waste-free production is also in the interest of preventive quality management, even if the purpose has so far been to minimize failure costs. Proven methods in quality management are, on the one hand, the Failure Mode and Effects Analysis (FMEA), the aim of which is to minimize the slip-through of defective parts to the customer by reducing the occurrence of defects and increasing its detection. The failure process matrix (FPM), which is used in particular for assembly processes, also assesses the financial benefits of earlier failure detection in the process. In the context of advancing climate change, many companies are focusing on ecological interests in addition to the previously predominantly monetary interests. The focus is on reducing CO_2-emissions across the entire value chain, as these are considered to be the main drivers of global warming. The focus of this paper is to link the two areas of quality assurance and CO_2 balancing of production processes by developing a software-based tool on Microsoft Excel. The tool uses automated evaluations of FMEA reports and operational data to calculate failure costs and corresponding emissions. The best outcome of a failure, either through scrap or rework, is evaluated and recommended considering both financial and environmental standpoints. Additionally, the tool also evaluates which quality activity would contribute the most towards carbon mitigation strategies, and where there is potential in the process with regards to CO_2 emissions and failure costs further mitigation. The tool offers companies an auxiliary and complementary support when accounting for environmental aspects concerning process failures, endorsing the vision that quality activities and environmental protection are fundamentally associated.

Keywords: Failure Costs, CO_2-Emissions, Quality Activities, FMEA, Ultra-Efficiency

1. Introduction

The production industry lies in the convergence of material and energy consumption. While energy systems gradually lessen their dependence on non-renewable sources, the manufacturing sector is correspondingly focusing on decreasing the preventable overconsumption of energy and material resources. Material efficiency is a key element of sustainable manufacturing processes. To produce efficiently with as little energy and material use as possible can be accomplished through different approaches, such as through recycling and re-using materials; and through reducing yield losses in materials manufacturing systems. Production failures, such as process rejects, scrap or defective items, which already have or potentially will adversely affect productivity, can be avoided and detected through the implementation of quality activities. Quality preventive and corrective actions can ensure process efficiency and effectiveness, without compromising sustainability and carbon mitigation potentials (Lindström et al., 2019; Sheehan et al., 2016; Waltersmann et al., 2019)

2. Literature Review

Both quality control and sustainability focuses on long-term goals and on maintaining performance achievements through similar paths such as waste elimination and zero-defect manufacturing systems. Concerning manufacturing companies, faulty actions within production processes result in defective parts and products, such as scrapped and reworked pieces. The implementation of quality control actions is fundamental to decreasing production failures and reducing costs through the early detection of defective units before they reach downstream production stages. This is particularly important to the avoidance of waste and achieving compliance with environmental regulations and policies concerning emissions. (Eger et al., 2018; Hillmann et al., 2014; Wiengarten & Pagell, 2012).

2.1. Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is one of the most widely used methods in the manufacturing industry to identify potential failures, assess their impact on the process, and plan for corrective actions. The central objective of FMEA is to minimize failures delivered to the customer, ideally by eliminating failure occurrence or by detection. Through this methodology, products and processes are evaluated to minimize the risks of occurrence of potential failure modes, with an emphasis on assuring the safety and security of workforces and systems (AIAG & VDA, 2019; Amrutha et al., 2021).

FMEA is a structured risk analysis method that also provides a prioritization of the failures that ensue. The first step is the identification of potential failure modes and the determination of their effect on the one hand and their causes on the other hand. The FMEA methodology defines the risk priority of failure modes through the Action Priority (AP), which can be looked up in tables based on the Severity (S), Occurrence (O), and Detection (D) of an analyzed failure. S is the severity measurement of the most serious failure effect for a given failure mode, O is a measure of the effectiveness of the prevention control in avoiding a given failure mode from occurring, and D is an estimated measure of the effectiveness of the detection control to reliably demonstrate the failure cause or failure mode (AIAG & VDA, 2019; Wu et al., 2014)

Environmental extensions and adaptations of FMEA have also been studied. The environmental applications of the FMEA focuses on determining the environmental impacts caused by technical failures and process non-conformities, assuming that failure modes from production processes are also a burden for the environment, negatively affecting the process eco-efficiency. Applying the FMEA methodology to environmental risk assessment, many different approaches for adaptations of the RPN calculation are frequently studied (Oliveira et al., 2020; Roszak et al., 2015; Yen & Chen, 2005) These adaptations, however, do not directly address the environmental impact in regards to CO_2 emissions generated through production failures from the manufacture industry.

2.2. Failure Process Matrix

The FPM is an effective alternative of the FMEA in assembly processes and is targeted at the optimization of complex mass production processes. The methodology consists of three analysis steps. Initially, the whole process chain is documented and divided into individual process steps. Any failure that ensues during the process chain is documented and linked to the corresponding process step, together with its potential failure detection. The error detection distance is a direct parameter of financial costs. The longer it takes, in terms of process steps, to notice a failure or to fix it, the more costs arise. Furthermore, it is also possible to show if the error rate increases during the assembly process. Consequently, a matrix is created that allows rapid visualization of potential failures and their corresponding detection possibility through prevention controls (Henke, 2016; Hillmann et al., 2014; Schloske, 2016; Schloske & Henke, 2006).

3. Approach for the calculation of a combined reduction potential of failure costs and CO_2-emissions

The tool calculates and evaluates optimizations of prevention and detection controls, evaluates and proposes the best internal outcome of each failure – either scrap or rework -, and additionally provides an assessment regarding early failure detection. For the successful functionality of the tool, the input of some process parameters is required. Due to a better understanding, these parameters are classified into four categories, considering their initial source of information: material, energy, operational and failure.

Material-related parameters refer to all material input to the process; i.e. material feedstock. Information such as quantity, cost and associated carbon footprint of each manufacturing component is relevant for further calculations of material-related costs and CO_2-emissions. Energy-related parameters refer to all information that comprises energy consumption and energy costs from the production process. Equally relevant is the input of all energy sources the company operates its process on, as well as the share composition of each source on the energy mix. Each energy source has an associated emissions factor that indicates the energy-related CO_2-emissions potential.

Operational parameters refer to all information that provides a better assessment of the structure, conditions, and boundaries of the production process, such as total batch size and cost of rework-time. The input of the list of steps from the manufacturing process is essential for understanding the organizational structure of the process. Additionally, the association of each machine and each manufacturing component to their corresponding process step is further required. This information binds material and energy data to individual process steps, and is the central requirement for the assessment of material and energy efficiency of the process, as well as material- and energy-related costs and CO_2-emissions.

Failure-related parameters are sourced directly from an FMEA. The tool provides a built-in system for the construction of the FMEA from the very beginning, and also supports the manual import of an already existent FMEA from APIS IQ-Software. FMEA report provides the foundation for the calculations of number of defective items generated by each failure, besides a comparative analysis of all subsequent quality activities implemented. The documentation of the process step in which each failure was first detected by quality controls is extracted from the FPM methodology, and is also an additional input requirement. Since components were previously assigned to process steps, the tool sources from FMEA the information of on which process step a failure has first occurred and automatically compares it to the process step it was detected. This analysis evaluates which machines the defective item has previously gone through, and how many components have been previously assembled together up until the failure detection. This information provides a valuable assessment of the optimizations and improvements the system has gone through, and enables the quantification of various evaluation parameters regarding further implementation of quality activities and their potential reductions of costs and CO_2-emissions.

3.1. Assessment of failure costs

Failure costs are calculated differently for each failure, depending on the process step it was discovered and on its outcome. Scrap costs account for the loss of material and energy gone to waste because of a process failure, as shown in Equation 1.

$$CS_i\ [€] = (CM_i + CE_i) \times N_{D_i} \tag{1}$$

where CS_i is the expected failure cost if all detected broken units generated by failure *i* were to be scrapped, in €; CM_i is the cost of material of one defective unit generated by failure *i*, in €; CE_i is the cost of energy for the manufacture of one defective unit generated by failure *i*, in €; and ND_i is the total number of defective units that were detected by quality actions within production, in reference of failure *i*.

However, before outright scrapping defective units, an evaluation of the potential rework costs is an important and influential comparative information. This calculation and assessment offer a better outlook of the cost-benefits on the decision-making of potential failure outcomes.

$$CR_i\ [€] = (CRT_i + CEM_i) \times N_{D_i} \tag{2}$$

where CR_i is the expected failure cost if all defective units generated by failure *i* were to be reworked, in €; CRT_i is the cost of rework-time per defective unit caused by failure *i*, in €; CEM_i is the cost of extra materials for the correction of each defective unit caused by failure *i*, in €; and ND_i is the total number of defective units that were detected by quality actions within production, in reference of failure *i*.

3.2. Assessment of CO_2-emissions

Whenever a failure ensues, the cumulative energy consumption of all machines previously utilized up until the step in which the failure was detected is described by Equation 3. This information is the foundation for the calculation of energy-related CO_2-emissions, and also takes into account the dynamic composition of the energy mix supplied by different energy sources.

$$EE_i\ [kgCO_2e] = \frac{EF_{mix} \times E_i}{N \times 1.000} \tag{3}$$

where EE_i is the cumulative energy-related CO_2e emissions for the manufacture of a single discovered defective unit generated by failure *i*, in $kgCO_2e$; EF_{mix} is the emissions factor of the energy mix, in gCO_2e/kWh; E_i is the cumulative energy consumption of machines up until the process step in which failure *i* was detected, in kWh; *N* is the total batch size; and 1.000 is the conversion factor from gram to kilogram.

When accounting for emissions, the carbon footprint of all material inputs to the process must also be considered. The carbon footprint refers to all upstream emissions that have already taken place before their introduction as the starting components of the assembly process. These materials have been either extracted from nature or recycled from other processes, and potentially underwent one or many different transformations that changed their chemical, biological and physical characteristics, during which different volumes of CO_2 were released to the atmosphere. The calculation for the material-related CO_2-emissions of one defective unit is given by Equation 4.

$$\sum_{i=1}^{n} ME_i \ [kgCO_2e] = \frac{N_{C_i} \times CF_{C_i} + \ N_{C_{i+1}} \times CF_{C_{i+1}} + \cdots + N_{C_n} \times CF_{C_n}}{1.000} \tag{4}$$

where ME_i is the cumulative carbon footprint for the production of a defective unit up to the process step in which the failure *i* was detected, in $kgCO_2e$; N_{Ci} is the quantity of each component; CF_{Ci} is the individual carbon footprint of each component, in gCO_2e; *n* represents the failure detection step; and 1.000 is the conversion factor from gram to kilogram.

Therefore, the quantification of the total emissions of a failure, if the defective units were to be scrapped is given by Equation 5.

$$EMS_i \ [kgCO_2e] = (EE_i + ME_i) \times N_{D_i} \tag{5}$$

where the EMS_i is the total CO_2e emissions if all detected broken units generated by failure *i* were to be scrapped, in $kgCO_2e$; EE_i is the energy-related emissions of one defective unit generated by failure *i*, in $kgCO_2e$; ME_i is the material-related emissions of one defective unit generated by failure *i*, in $kgCO_2e$; and ND_i is the total number of detected broken units generated by failure *i*.

The total corresponding CO_2-emission of a failure, if the defective units were to be reworked back into conformity instead of outright scrapped, is given by Equation 6.

$$EMR_i[kgCO_2e] = (EE_i + EME_i) \times N_{D_i} \tag{6}$$

where EMR_i is the total emissions CO_2e emissions if all detected broken units generated by failure *i* were to be reworked back into conformity, in $kgCO_2e$; EE_i is the energy-related emissions of one defective unit generated by failure *i*, in $kgCO_2e$; EME_i is the material-related emissions of replacement parts due to rework, in $kgCO_2e$; and ND_i is the total number of detected broken units generated by failure *i*.

3.3. Assessment of failure outcome

Although the environmental perspective might relate to the financial perspective in regards to the internal failure outcome, either scrap or rework, the decision of which standpoint is more relevant concerning each specific failure is often hard to account for. This work proposes a revaluation of the definition of a failure outcome, considering both financial and environmental assessments. For the revaluation, two conditions must be satisfied.

The first condition relates to the comparison of potential cost of scrap and potential cost of rework due to the same failure. A comparative analysis of the potential failure costs for both failure outcomes is first evaluated. The financially-oriented failure outcome is then defined by the one with the lowest cost. The revaluation proposes, however, that if the absolute difference between both costs is less than a pre-defined percentage of extra failure costs (*EFC*) allowed by the company, a change of failure outcome is recommended. The EFC limit refers to the maximum extra amount of money that the company is willing to pay for, in order to potentially reduce emissions due to a change of a failure's outcome. The percentage of the maximum allowed extra internal failure costs is pre-set by the company and input to the tool. Equation 7 verifies if the potential change of the failure's outcome is within this percentage limit.

$$|CR_i - CS_i| \ \leq \ min(CR_i; CS_i) \times EFC \tag{7}$$

where the absolute difference between cost of rework CR_i and cost of scrap *CSi* of a given failure *i*, in €, is equal or less than the lowest value multiplied by cut-off limit of extra failure cost *EFC*, in percentage.

If the first condition is satisfied, the second condition must also be evaluated. Correspondingly to failure costs, a comparative analysis of the potential emissions for both failure outcomes is subsequently evaluated. The second revaluation condition furthermore proposes that some failures might be worth a change of outcome, even if at the expense of extra failure costs, if the altered outcome generates a significantly reduction of emissions, i.e. the minimum expected reduction of emissions (*MRE*). The MRE limit percentage refers to the minimum reduction of emissions expected by the company, in order to justify and validate the extra failure cost expending. The MRE limit is calculated as described by Equation 8.

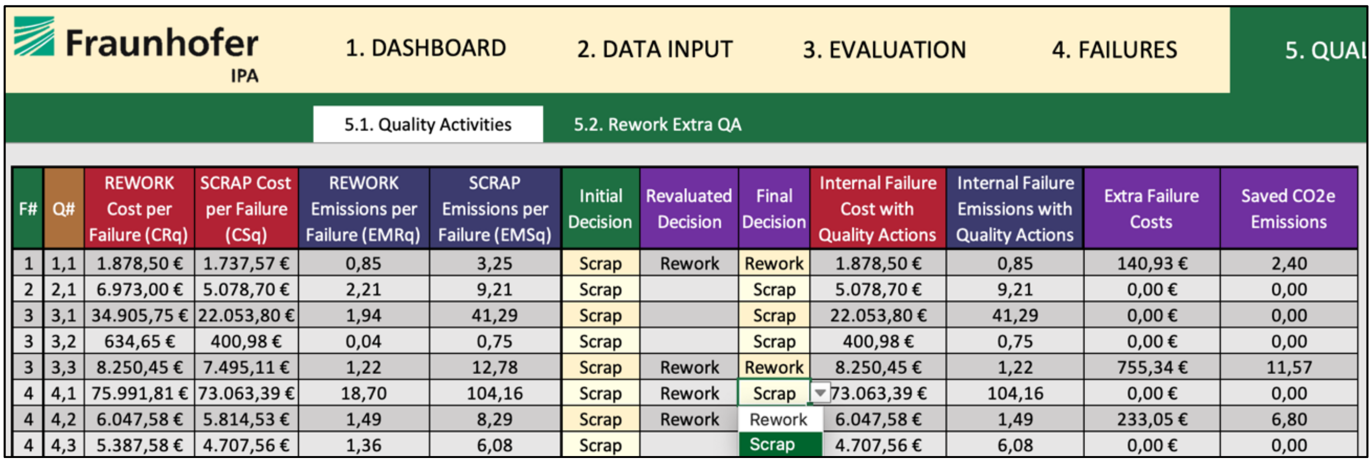
$$1 - \frac{min(EMR_i; EMS_i)}{max(EMR_i; EMS_i)} \geq MRE \tag{8}$$

where the comparative reduction of rework-related emissions EMR_i and scrap-related emissions EMS_i of a given failure *i*, in $kgCO_2e$, is equal or greater than the minimum reduction of emissions expected by the company, in percentage.

When both conditions are satisfied, as they are both equally important, the best recommended outcome for the particular process failure is automatically calculated by the tool and given by the outcome that generated fewer emissions. When either one or both conditions are not satisfied, the best-recommended outcome for the process failure is the one that generates fewer costs. This evaluation restricts the financial impact of a different failure outcome to a pre-defined percentage given by the company, which can highly differ concerning internal organizational strategies. At the same time, it quantifies the failures in which a change of outcome would be significant enough in terms of emissions, so that the economic impact can be environmentally reasonable. Ultimately, this revaluation allows companies to account for the extra expenditure on failure costs as an investment in CO_2-emissions mitigation and a move closer towards sustainable production systems.

4. Results

The evaluation of a potential change of failure outcome and its impact on failure costs and emissions is automatically calculated by the tool. The tool calculates and presents the best outcome for each failure as a default. However, due to internal guidelines or the production structure of the company, the final decision regarding each failure outcome can be selected and altered. The tool will automatically recalculate both costs and emissions for the reselected failure outcome. Additionally, if even within the pre-set boundaries limitation of extra failure costs, the company still considers the extra spending on failure costs of a specific failure to be too high, it can manually reselect its outcome as well, as shown in Figure 1.

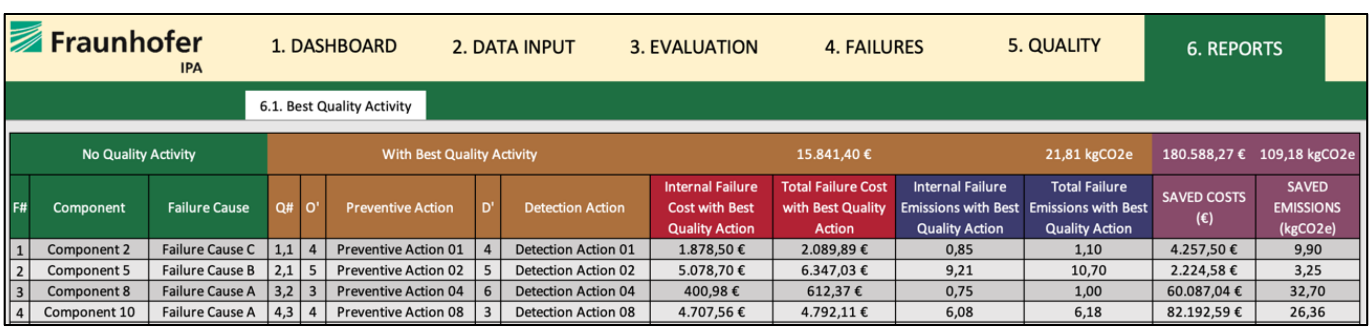


F#	Q#	REWORK Cost per Failure (CRq)	SCRAP Cost per Failure (CSq)	REWORK Emissions per Failure (EMRq)	SCRAP Emissions per Failure (EMSq)	Initial Decision	Revaluated Decision	Final Decision	Internal Failure Cost with Quality Actions	Internal Failure Emissions with Quality Actions	Extra Failure Costs	Saved CO2e Emissions
1	1,1	1.878,50 €	1.737,57 €	0,85	3,25	Scrap	Rework	Rework	1.878,50 €	0,85	140,93 €	2,40
2	2,1	6.973,00 €	5.078,70 €	2,21	9,21	Scrap		Scrap	5.078,70 €	9,21	0,00 €	0,00
3	3,1	34.905,75 €	22.053,80 €	1,94	41,29	Scrap		Scrap	22.053,80 €	41,29	0,00 €	0,00
3	3,2	634,65 €	400,98 €	0,04	0,75	Scrap		Scrap	400,98 €	0,75	0,00 €	0,00
3	3,3	8.250,45 €	7.495,11 €	1,22	12,78	Scrap	Rework	Rework	8.250,45 €	1,22	755,34 €	11,57
4	4,1	75.991,81 €	73.063,39 €	18,70	104,16	Scrap	Rework	Scrap	73.063,39 €	104,16	0,00 €	0,00
4	4,2	6.047,58 €	5.814,53 €	1,49	8,29	Scrap	Rework	Rework	6.047,58 €	1,49	233,05 €	6,80
4	4,3	5.387,58 €	4.707,56 €	1,36	6,08	Scrap		Scrap	4.707,56 €	6,08	0,00 €	0,00

Figure 1. Revaluation of failure outcome

Once the final decision of failure outcome is reached, the tool automatically recalculates both total failure costs and total failure emissions for each quality activity reported on the FMEA, considering each failure and each outcome. This direct comparison offers a better overview of which is the best quality activity to be implemented.

As shown in Figure 2, the tool automatically selects the best quality activity for each failure considering the lowest associated total failure costs and total failure emissions. Additionally, the tool provides an overview of the total reduction of failure costs due to the implementation of the selected quality activities, and their corresponding avoidance of CO_2-emissions.



No Quality Activity			With Best Quality Activity						15.841,40 €		21,81 kgCO2e	180.588,27 €	109,18 kgCO2e
F#	Component	Failure Cause	Q#	O'	Preventive Action	D'	Detection Action	Internal Failure Cost with Best Quality Action	Total Failure Cost with Best Quality Action	Internal Failure Emissions with Best Quality Action	Total Failure Emissions with Best Quality Action	SAVED COSTS (€)	SAVED EMISSIONS (kgCO2e)
1	Component 2	Failure Cause C	1,1	4	Preventive Action 01	4	Detection Action 01	1.878,50 €	2.089,89 €	0,85	1,10	4.257,50 €	9,90
2	Component 5	Failure Cause B	2,1	5	Preventive Action 02	5	Detection Action 02	5.078,70 €	6.347,03 €	9,21	10,70	2.224,58 €	3,25
3	Component 8	Failure Cause A	3,2	3	Preventive Action 04	6	Detection Action 04	400,98 €	612,37 €	0,75	1,00	60.087,04 €	32,70
4	Component 10	Failure Cause A	4,3	4	Preventive Action 08	3	Detection Action 08	4.707,56 €	4.792,11 €	6,08	6,18	82.192,59 €	26,36

Figure 2. Definition of best quality activity for each reported failure

5. Discussion and outlook

The tool was constructed to directly evaluate internal failure costs and their corresponding CO_2-emissions, by an automated analysis of operational data and a process FMEA form. The tool calculates failure costs and emissions for both possible internal outcomes of a process failure: scrap and rework. Quality preventive and corrective actions can be implemented in order to ensure process efficiency and effectiveness, without compromising the sustainability and carbon mitigation potentials. Their effectiveness and potential for reduction of costs and emissions have been calculated and evaluated.

This work has evaluated the environmental impact of process failures and analyzed how it relates to failure costs. Either through early failure detection, preventive controls, detection controls, or through the revaluation of a detected failure outcome, environmental protection is fundamentally associated with the quality assurance of manufacturing processes. Quality activities that represent a greater reduction of failure costs are usually associated with greater reductions of CO_2-emissions, as both comprises material- and energy-related parameters. In order to further mitigate emissions, some extra failure costs might be additionally allowed and accounted for as investments towards environmental protection, as long their associated avoidance of CO_2-emissions is relevant and meaningful enough for a balanced trade-off.

This work stops at the point where an association of reduction of internal failure costs and avoidance of CO_2e emissions through the implementation of quality activities has been presented, quantified, and evaluated. The logical next step would be to further investigate the impact of external failure costs and corresponding external CO_2-emissions, and their potential adaptability to the developed tool. This examination will further provide a better overview of the environmental impact of defective units arising from production failures.

Furthermore, this work has been limited to the presentation of the tool's potential of data output through generic examples of operational parameters and failure reports. What follows is the application and testing of the tool for the evaluation of an actual production process.

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