AN EVALUATION OF ECONOMICAL AND ENERGETIC SAVINGS DEPENDING ON THE ARRANGEMENT OF QUALITY CONTROL STEPS WITHIN THE PRODUCTION

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Abstract: In order to avoid that faulty units reach following production stages, and cause further costs and energy consumption, quality control steps need to be realised. Within the production, many different arrangements of quality control steps are possible. This paper describes an evaluation of costs and energy consumption depending on the arrangement of quality control steps based on a sample process sequence. The results of the evaluation show the different possible economical and energetic savings. Moreover the paper shows how far the cost optimal arrangements differ from the energy optimal arrangements.

Keywords: Quality Assurance, Resource Efficiency, Sustainable Production

1. INTRODUCTION

The assessed consumption of services and goods of an enterprise caused by faulty actions is referred to as effort for nonconformity (Kamiske and Brauer, 2008). The monetary effects of the effort for nonconformity are summarised under the term failure costs (Melzer-Ridinger, 2008). This term can be subdivided into internal and external failure costs (Berk and Berk, 2000; Borror, 2009). Internal failure costs, which are caused by the non-compliance of internal quality requirements, represent a share of about 45 percent of the quality costs in enterprises (Wannenwetsch, 2010), which in turn have a share of around 5-8 percent of the turnover of electrical and mechanical engineering companies (Krokowski, 1998). The total turnover of German mechanical engineering companies amounted to approximately 206.8 Billion Euro in 2012 (VDMA, 2013). Therefore, internal failures caused around 6 Billion Euro of internal failure costs in German mechanical engineering companies in 2012.

Besides the increased costs, internal failures also cause increased energy consumption. Usually, most of the energy is produced from fossil fuels (e.g. coal, natural gas, oil). A big challenge of humankind is the global warming effect, implicating accidents in nature (Seliger, 2007). The use of fossil fuels leads to an increased emission of greenhouse gases, which in turn are responsible for the global warming effect. The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty. The goal of the Framework Convention is the stabilisation of greenhouse gas emissions at the 1990 level (Fisher, 2004). To reach this goal, it is very important to minimise the energy consumption. In Germany, industry had a share of approximately 40 percent of the total energy consumption in 2005 (Neugebauer, *et al.*, 2008). In industry, most of the energy consumption can be decreased within the production. Compared to the costs, the energy consumption caused by internal failures has not yet been considered in detail. Thus, the energy consumption is explicitly taken into account within the evaluation process.

Within the production, failures can be reduced by implementing different quality improvement methods (e.g. Poka Yoke, 5S, Investigations of machine capability and process capability). Each of these methods has its specific capability to reduce failures. In this vein, failures are reduced but still occur. In order to avoid that faulty units reach downstream production stages and cause further costs and energy consumption, quality control steps are realised within the production. However, quality control steps during the production cause a considerable amount of costs and additional energy consumption. Production planners have to decide about the arrangement of quality control steps within the production. Due to the high number of production stages, many different arrangements of quality control steps are possible. The crucial question is how many costs and how much energy can be saved with an optimised arrangement of quality control steps. Moreover it is important to know how far the cost optimal arrangement differs from the energy optimal arrangement.

In order to investigate this issue, scientists from Bayreuth University and Fraunhofer Project Group Process Innovation determined the specific costs and energy consumption for possible arrangements of quality control steps for several scenarios based on a sample process sequence. The evaluation process and results are presented subsequently.

2. METHODOLOGY

2.1. Development of the sample process sequence

The first step was the development of a sample process sequence. This process sequence has to comply with different requirements: First of all the sample process sequence must include several production stages. The higher the number of production stages, the higher the number of possible quality control steps as well as the number of different possible arrangements of implemented quality control steps. The accuracy of the evaluation increases with the number of different possible arrangements of quality control steps. Furthermore, the different production stages must represent manufacturing processes that are typically applied in mechanical engineering companies. This ensures a high practical orientation. As a result of these considerations, the following five production stages were chosen on the basis of several optimisation projects in mechanical engineering companies: Sawing, CNC Milling, Drilling, Cleaning and Assembly.

Within the sample process sequence optional quality control steps were integrated. These optional steps are placeholders and can be replaced with implemented quality control steps within the evaluation process. In case of the detection of a faulty unit at a quality control step, the faulty unit will be discarded. To ensure the conformity of common quality standards (e.g. ISO 9001:2008) a 100% incoming inspection and a 100% final inspection of all products were taken into account. Finally, specific properties were ascertained to the different production stages and quality control steps (e.g. cycle time, error frequency, costs). These properties were derived from literature review and experience based on several optimisation projects in mechanical engineering companies. The sample process sequence is shown in Figure 1.

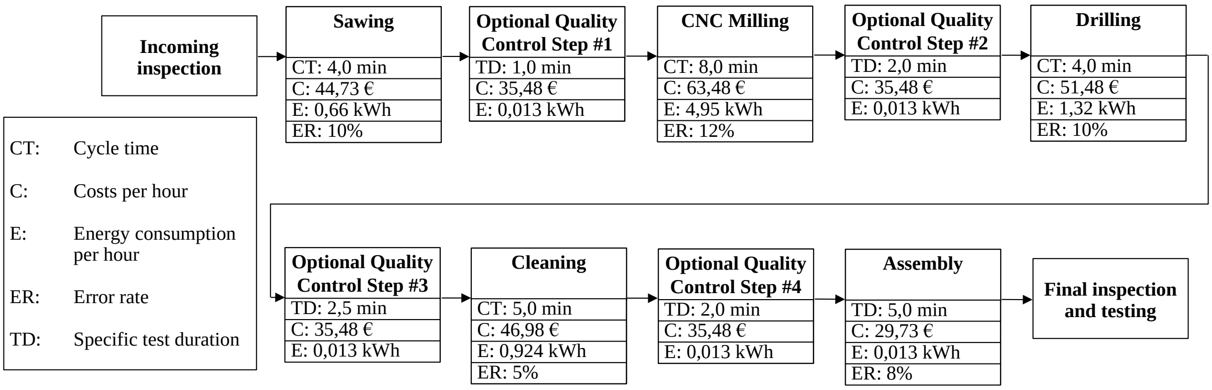

Fig. 1. Sample process sequence.

2.2. Generation of scenarios

The evaluation was performed for different possible scenarios. The scenarios differ in their assumptions about the quality improvements of the individual production stages QI_n caused by different implemented methods. The index n represents the production stage (Sawing: n=S, CNC Milling: n=M, Drilling: n=D, Cleaning: n=C, Assembly: n=A). Each quality improvement of each scenario is calculated from specific quality improvements QI_{s_m}. The index m represents the sequential number of the specific quality improvement. The specific quality improvements are estimations, based on several optimisation projects, and represent typical achievable quality improvements of different optimisation methods (e.g. 5S, Poka Yoke).

$$QI_n = 1 - ((1 - QI_{s\_1}) \cdot (1 - QI_{s\_2}) \cdot \ldots \qquad (1)$$

Ten various scenarios were generated. An overview of the different scenarios and their assumed quality improvements is given in table 1.

Table 1. Different scenarios and their general quality improvements.

	QI_S	QI_M	QI_D	QI_C	QI_A
Scenario 1	0,0%				
Scenario 2	10,0%				
Scenario 3	14,4%				
Scenario 4	16,2%	10,7%	7,9%	21,6%	13,5%
Scenario 5	7,8%	7,8%	6,9%	5,9%	13,8%
Scenario 6	40,0%	40,0%	0,0%	80,0%	0,0%
Scenario 7	95,0%	95,0%	0,0%	0,0%	0,0%
Scenario 8	10,0%	0,0%	0,0%	98,0%	0,0%
Scenario 9	0,0%	0,0%	99,0%	0,0%	0,0%
Scenario 10	0,0%	0,0%	0,0%	99,0%	99,0%

2.3. Arrangements of quality control steps

As already mentioned, the sample process sequence (shown in Figure 1) contains four placeholders, which can be replaced with implemented quality control steps. For the evaluation process, a full factorial experimental design was developed. The experiment contains two levels (quality control step is implemented or is not implemented) for each of the four factors. Thus, the experiment is a 2^4 full factorial experimental design with 16 factorial points. Each possible arrangement is a factorial point and is characterised with a four-digit code. Within the evaluation process, the costs and energy consumption of each factorial point were determined. The experimental design is shown in table 2.

Table 2. Experimental design.

	Arrangement Code															
	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
Optional Quality Control Step #1	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	✓	✓	✓	✓	✓	✓	✓	✓
Optional Quality Control Step #2	⊘	⊘	⊘	⊘	✓	✓	✓	✓	⊘	⊘	⊘	⊘	✓	✓	✓	✓
Optional Quality Control Step #3	⊘	⊘	✓	✓	⊘	⊘	✓	✓	⊘	⊘	✓	✓	⊘	⊘	✓	✓
Optional Quality Control Step #4	⊘	✓	⊘	✓	⊘	✓	⊘	✓	⊘	✓	⊘	✓	⊘	✓	⊘	✓

✓	Quality control step is implemented
⊘	Quality control step is not implemented

2.4. Determination of costs

Quality costs can be categorised into prevention costs, failure costs and appraisal costs (McCormick, 2002; Borror, 2009). Prevention costs are costs which are expended to prevent failures from being made (e.g. costs of quality-related trainings, costs of quality improvement projects) (Harrington, 1987). Quality control steps detect failures rather than preventing them. Therefore, the arrangement of implemented quality control steps has no influence on the prevention costs. Thus, the prevention costs were not considered within the evaluation process. As already mentioned in the introduction, failure costs can be subdivided into external failure costs and internal failure costs (Berk and Berk, 2000; Borror, 2009). External failure costs are incurred because products fail to conform to requirements or satisfy customer needs after being delivered to customer (Hansen and Mowen,

2011). The external failure costs do not depend on the arrangement of implemented quality control steps within the sample process sequence because a 100% final inspection of all products was taken into account. Therefore, the external costs were also not considered within the evaluation process.
Faulty actions within the production cause internal failure costs. As already mentioned, internal failure costs can be reduced by the realisation of quality control steps within the production. Quality control steps determine whether or not products conform to requirements. The costs for quality control steps are summarised under the term appraisal costs (Hansen and Mowen, 2011). To sum it up, the internal failure costs and the appraisal costs are depending on the arrangement of implemented quality control steps within the production. Therefore, these categories of costs were determined within the economical evaluation process.

Internal failure costs. The following section describes the determination of internal failure costs per produced unit, which can be sold to a customer. The index n represents the production stage (Sawing: n=S, CNC Milling: n=M, Drilling: n=D, Cleaning: n=C, Assembly: n=A).

The total internal failure costs C_f within the sample process sequence are equal to the sum of all internal failure costs of the individual production stages C_{fp_n}.

$$\mathrm{C_f = C_{fp\_S} + C_{fp\_M} + C_{fp\_D} + C_{fp\_C} + C_{fp\_A}} \tag{2}$$

In case of an implemented quality control step previous to the considered production stage: The internal failure costs of a production stage C_{fp_n} are calculated from the error rate of the considered production stage ER_{pr_n} and the added value V_{add_n}.

$$\mathrm{C_{fp\_n} = ER_{pr\_n} \cdot V_{add\_n}} \tag{3}$$

In case of no implemented quality control step previous to the considered production stage: The internal failure costs of a production stage C_{fp_n} is calculated from the error rate of the considered production stage ER_{pr_n}, the added value V_{add_n}, the rate of faulty units which are delivered to the considered production stage ER_{d_n} and the process costs of the considered production stage C_{pr_n}.

$$\mathrm{C_{fp\_n} = ER_{pr\_n} \cdot \left(1 - ER_{d\_n}\right) \cdot V_{add\_n} + ER_{d\_n} \cdot C_{pr\_n}} \tag{4}$$

The error rate of the considered production stage ER_{pr_n} is calculated from the error rate of the considered production stage without any implementation of quality improvement methods ER_n and the quality improvement of the considered production stage QI_n.

$$\mathrm{ER_{pr\_n} = ER_n \cdot (1 - QI_n)} \tag{5}$$

The added value V_{add_n} is equal to the sum of the process costs of the considered production stage C_{pr_n} and the costs of all upstream production stages C_{pr_n-1}, C_{pr_n-2}, ... The upper bound of summation b depends on the considered production stage (Sawing: b=0, CNC Milling: b=1, Drilling: b=2, Cleaning: b=3, Assembly: b=4).

$$\mathrm{V_{add\_n} = C_{pr\_n} + \sum_{\mathit{i}=1}^{b} C_{pr\_n-i}} \tag{6}$$

The process costs of a production stage C_{pr_n} is calculated from the specific costs per hour C_n and the cycle time CT_n of a production stage. The specific costs per hour C_n include all costs of the processing of the considered production stage in one hour (e.g. staff costs, machinery costs).

$$\mathrm{C_{pr\_n} = C_n \cdot CT_n} \tag{7}$$

In case of an implemented quality control step previous to the next upstream production stage: The rate of faulty units, which are delivered to the considered production stage ER_{d_n} is equal to the error rate of the next upstream production stage ER_{pr_n-1}.

$$\mathrm{ER_{d\_n} = ER_{pr\_n-1}} \tag{8}$$

In case of no implemented quality control step previous to the next upstream production stage: The rate of faulty units which are delivered to the considered production stage ER_{d_n} is calculated from the rate of faulty units which are delivered to the next upstream production stage ER_{d_n-1} and the error rate of the next upstream production stage ER_{pr_n-1}.

$$\mathrm{ER_{d\_n}} = \mathrm{ER_{d\_n-1}} + \mathrm{ER_{pr\_n-1}} \cdot (1 - \mathrm{ER_{d\_n-1}}) \tag{9}$$

Appraisal costs. The following section describes the determination of appraisal costs per produced unit, which can be sold to a customer. The index r represents the sequential number of implemented quality control step.

The total appraisal costs C_a within the sample process sequence are equal to the sum of all appraisal costs of the implemented quality control steps C_{aq_r}.

$$\mathrm{C_a} = \mathrm{C_{aq\_1}} + \mathrm{C_{aq\_2}} + \ \ldots \tag{10}$$

The appraisal costs of an implemented quality control step C_{aq_r} is calculated from the specific costs per hour C_r, the test frequency TF_r and the necessary test duration TD_{a_r}.

$$\mathrm{C_{aq\_r}} = \mathrm{C_r} \cdot \mathrm{TF_r} \cdot \mathrm{TD_{a\_r}} \tag{11}$$

Within the sample process sequence each quality control step checks 100% of the units. Therefore, the test frequency TF_r is equal to 100%. The necessary test duration TD_{a_r} depends on the arrangement of quality control steps. TD_{a_r} characterises the duration to check all the product characteristics that have been added by all upstream production stages since the last implemented quality control step. The specific test duration of an optional quality control step TD_r describes the duration to check the product characteristics of the next upstream production stage.

Hence, the necessary test duration of an implemented quality control step is equal to the sum of the specific test duration of the considered quality control step TD_r and the specific test duration of all optional quality control steps $\mathrm{TD_{opt}}$ up to the next implemented quality control step.

$$\mathrm{TD_{a\_r}} = \mathrm{TD_r} + \mathrm{TD_{opt1}} + \mathrm{TD_{opt2}} + \ \ldots \tag{12}$$

2.5. Determination of energy consumption

In addition to internal failure costs, faulty actions within the production cause increased energy consumption. The energy consumption caused by faulty actions within the production is summarised under the term internal failure energy consumption. Internal failure energy consumption can be reduced by the realisation of quality control steps within the production. However, implemented quality control steps cause an increased energetic effort. This effort is summarised under the term appraisal energy consumption.

The internal failure energy consumption and the appraisal energy consumption are depending on the arrangement of implemented quality control steps. Therefore, these categories of energy consumption were determined for possible arrangements of quality control steps in the described scenarios based on the sample process sequence.

Internal failure energy consumption. The following section describes the determination of internal failure energy consumption per produced unit, which can be sold to a customer. The index n represents the production stage (Sawing: n=S, CNC Milling: n=M, Drilling: n=D, Cleaning: n=C, Assembly: n=A).

The total internal failure energy consumption E_f within the sample process sequence is equal to the sum of all internal failure energy consumptions of the individual production stages E_{fp_n}.

$$\mathrm{E_f} = \mathrm{E_{fp\_S}} + \mathrm{E_{fp\_M}} + \mathrm{E_{fp\_D}} + \mathrm{E_{fp\_C}} + \mathrm{E_{fp\_A}} \tag{13}$$

In case of an implemented quality control step previous to the considered production stage: The internal failure energy consumption of a production stage E_{fp_n} is calculated from the error rate of the considered production stage ER_{pr_n} and the added energy E_{add_n}.

$$\mathrm{E_{fp\_n}} = \mathrm{ER_{pr\_n}} \cdot \mathrm{E_{add\_n}} \tag{14}$$

In case of no implemented quality control step previous to the considered production stage: The internal failure energy consumption of a production stage E_{fp_n} is calculated from the error rate of the considered production stage ER_{pr_n}, the added energy E_{add_n}, the rate of faulty units which are delivered to the considered production stage by the previous process ER_{d_n} and the energy consumption of the considered production stage E_{pr_n}.

$$\mathrm{E_{fp\_n}} = \mathrm{ER_{pr\_n}} \cdot \left(1 - \mathrm{ER_{d\_n}}\right) \cdot \mathrm{E_{add\_n}} + \mathrm{ER_{d\_n}} \cdot \mathrm{E_{pr\_n}} \tag{15}$$

The added energy E_{add_n} is equal to the sum of the energy consumption of the considered production stage E_{pr_n} and the energy consumption of all upstream production stages E_{pr_n-1}, E_{pr_n-2}, ... The upper bound of summation b depends on the considered production stage (Sawing: b=0, CNC Milling: b=1, Drilling: b=2, Cleaning: b=3, Assembly: b=4).

$$E_{add\_n} = E_{pr\_n} + \sum_{i=1}^{b} E_{pr\_n-i} \tag{16}$$

The process energy consumption of a production stage E_{pr_n} is calculated from the specific energy consumption per hour E_n and the cycle time CT_n of a production stage. The specific energy consumption per hour E_n includes all energy consumption of the processing of the considered production stage per hour (e.g. electrical energy for machining, electrical energy for lighting).

$$E_{pr\_n} = E_n \cdot CT_n \tag{17}$$

Appraisal energy consumption. The following section describes the determination of appraisal energy consumption per produced unit, which can be sold to a customer. The index r represents the sequential number of implemented quality control step.

The total appraisal energy consumption E_a within the sample process sequence is equal to the sum of all appraisal energy consumptions of the implemented quality control steps E_{aq_r}.

$$E_a = E_{aq\_1} + E_{aq\_2} + \dots \tag{18}$$

The appraisal energy consumption of an implemented quality control step E_{aq_r} is calculated from the specific energy consumption per hour E_r, the test frequency TF_r and the necessary test duration TD_{a_r}.

$$E_{aq\_r} = E_r \cdot TF_r \cdot TD_{a\_r} \tag{19}$$

As already mentioned, the test frequency TF_r is equal to 100%.

3. RESULTS

The total internal failure costs C_f and the total appraisal costs C_a are depending on the arrangement of implemented quality control steps within the production. Moreover, the total internal failure costs C_f are also depending on the scenario. The total internal failure costs C_f and the total appraisal costs C_a are summarised under the term evaluated costs C_e. The chart in Figure 2 shows a section of the different evaluated costs C_e depending on the arrangement of implemented quality control steps for each scenario. Furthermore the chart shows the average of maximum costs and the average of minimum costs of the scenarios.

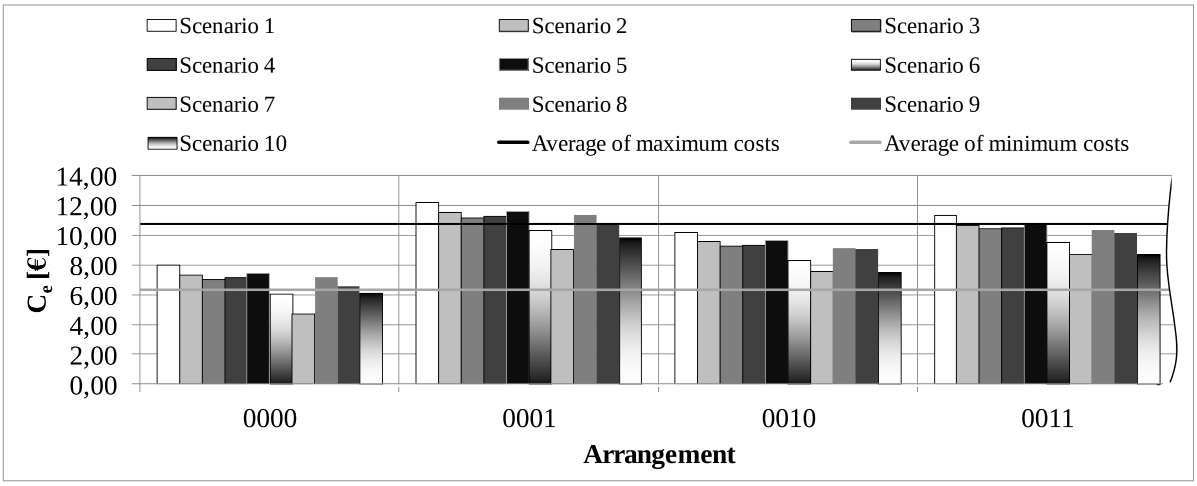

Fig. 2. Evaluated costs C_e depending on the arrangement of implemented quality control steps for each scenario.

As well as the total internal failure costs C_f and the total appraisal costs C_a, the total internal failure energy consumption E_f and the total appraisal energy consumption E_a are depending on the arrangement of implemented quality control steps. Moreover, the total appraisal energy consumption is also depending on the scenario. The total internal failure energy consumption E_f and the total appraisal energy consumption E_a are summarised under the term evaluated energy consumption E_e. The chart in Figure 3 shows a section of the different evaluated energy consumptions E_e depending on the arrangement of implemented quality control steps for each scenario. Furthermore the chart shows the average of maximum energy consumption and the average of minimum energy consumption of the scenarios.

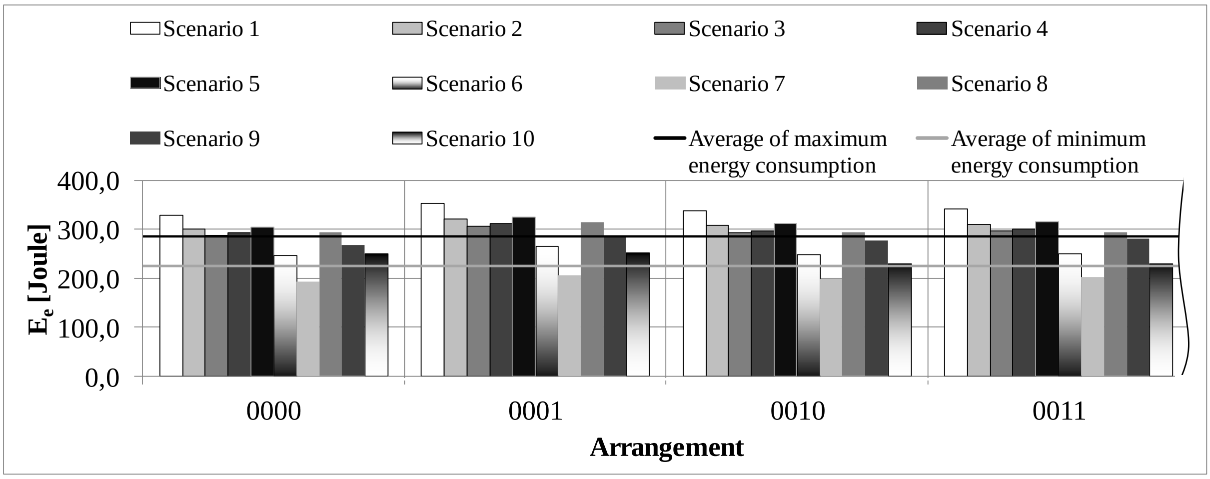

Fig. 3. Evaluated energy consumptions E_e depending on the arrangement of implemented quality control steps for each scenario.

Compared to the situation, that no quality control step is implemented (arrangement combination 0000), the costs and the energy consumption increase or decrease. The chart in Figure 4 provides an overview of maximum possible economical and energetic savings of each scenario compared to the situation that no quality control step is implemented. The range of different maximum possible economical savings reaches from 0.0 percent up to 12.9 percent. The average of maximum possible economical savings is 7.0 percent. The range of different maximum possible energetic savings reaches from 1.5 percent up to 32.0 percent. The average of maximum possible energetic savings is 17.9 percent.

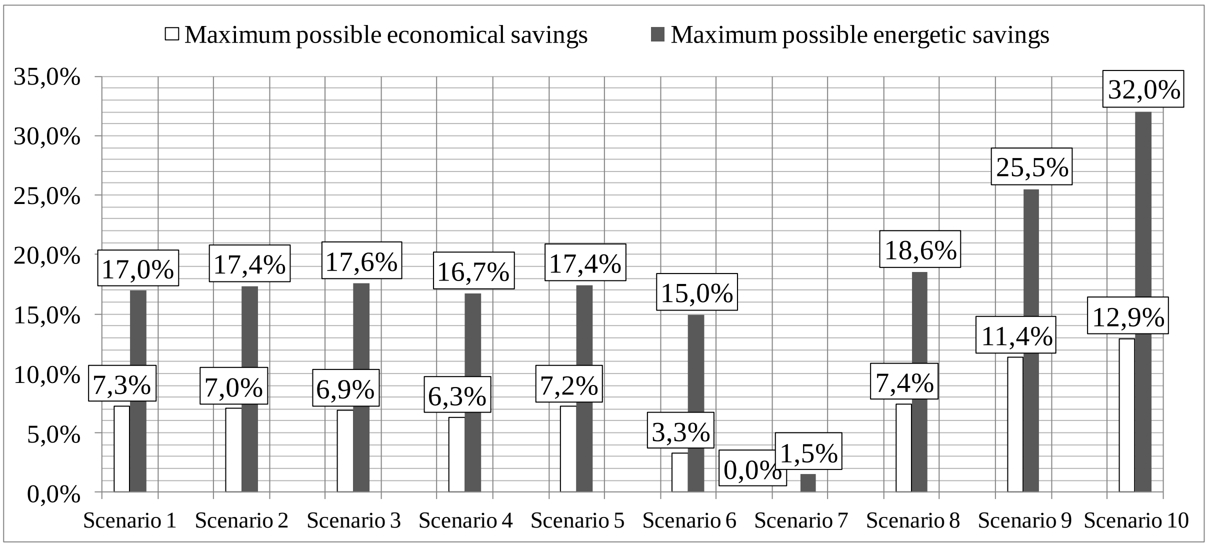

Fig. 4. Overview of the maximum possible economical and energetic savings of each scenario.

The final question to be asked is how far the cost optimal arrangement differs from the energy optimal arrangement of implemented quality control steps within the sample process sequence. Table 3 shows the cost optimal arrangement and the energy optimal arrangement for each scenario. In case of scenario 1, scenario 2, scenario 4 and scenario 5, the economical optimal arrangement is in conformity with the energy optimal arrangement. In case of the other six scenarios, the economical optimal arrangement is not in conformity with the energy optimal arrangement. Therefore, in 40 percent of all cases the cost optimal arrangement is equal to the energy optimal arrangement of quality control steps.

Table 3. Overview of cost optimal and energy optimal arrangements for each scenario.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Rate of Conformity
Cost optimal arrangement	1000	1000	1000	1000	1000	1000	0000	1000	1000	1000	
Energy optimal arrangement	1000	1000	1100	1000	1000	1100	1000	1110	1100	1110	
Conformity	✓	✓	⊘	✓	✓	⊘	⊘	⊘	⊘	⊘	40 %

4. CONCLUSION

The paper described the evaluation of costs and energy consumption depending on the arrangement of quality control steps for several scenarios. Furthermore the paper showed for the first time maximum possible economical and energetic savings depending on the arrangement of quality control steps for several scenarios compared to the situation, that no quality control step is implemented. The evaluation is based on a sample process sequence. According to the different scenarios, the average of maximum economical savings is 7.0 percent and the average of maximum energetic savings is 17.9 percent. Moreover, the evaluation indicated that in 40 percent of all cases the cost optimal arrangement of quality control step is in conformity with the energetic optimal arrangement. As part of future research the results will be verified by pilot applications. Furthermore, proportions between internal failure costs and appraisal costs as well as proportions between internal failure energy consumption and appraisal energy consumption depending on the arrangement of quality control steps will be evaluated. In addition, optimisation methods to achieve conformity of cost optimal arrangements and energy optimal arrangements will be developed.

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