Contributions for Cost Optimized Selection of Quality Inspection Methods for Surface or Depth Machining Defects

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Abstract
One of the major decision which the manufacturing process designer must take in consideration, knowing the annual production volume and average volume of the batches, is the tuning of the equipment used for product quality inspection, which must be specific manufactured (specialized or modular) or with a higher universality. The approach of scientific technical-economic criteria of this decision is detail explored in this paper, by exposing the theoretical side and the case study. In the next pages, will be presented the choosing of quality product inspection using the total costs used for finding surface and depth machining defects for two of the methods used: inspection with ultrasounds and inspection with penetrant liquids.

Keywords
surface defects, penetrant liquid, ultrasounds, quality inspection, cost

1. Introduction

In every type of human activity, it can be found a knowledge component whose main purpose is to reflect almost perfectly the real technological processes through various laws of progress, which then gives the possibility to improve in conformity with desired and possible performances.

World products are always accompanied by measurement and control activities of various properties and characteristics, which determines the product quality [1].

Product quality inspection by ultrasounds or penetrant liquids is not directly adding value to the product, this is done to approve the manufacturing process or the conformity of the characteristic imposed by the customer of manufacturer of the product. On the other way, product quality inspection results can have a direct influence over the managers, technological, constructive, conceptual, executional and maintenance decisions, verification being a reaction buckle (feedback) in every technological process for the product quality assurance.

From economic point of view, quality inspection is a non-productive time, which increases the cost of manufacturing, for this reason this process must be limited to an absolute necessarily in each process step of the product manufacturing.

These two methods allow the operator to identify or visualize surface or in depth macrostructural defects, that can have a major influence over the next technological process or assembly [2].

The paper presents a method to decide, from the cost point of view, from the start of the project, which is the best option that can be used in production based on the total cost of each process.

2. Optimization of Devices Selection in Terms of Total Costs for Product Quality Inspection

Quality of a product depends in fundamental way of the design and conception activity of the quality verification devices. In this way was determine that 80% [4] from product quality it is agreed in the conception or selection of the verification device. Only 20% from the quality can be influenced (good or bad) by the execution process performance [2].

Another method for determining the optimal quality inspection method, ultrasounds or penetrant liquids, can be done by using the next C_v relation, which takes in consideration other factors:

$$C_v = C_{pi} + n_p \left(N_{\frac{t}{v}} \times C_{o.ech} + C_S \right), \tag{1}$$

where C_{pi} are the costs for product verification process preparation, adding: design, C_p, and execution, C_{ex}, costs for the verification device/s, the software used to run the equipment and the setup costs, C_{set}; n_p is the number of verified pieces; $N_{t/v}$ is the time norm of verification operation for product quality;

$C_{o.ech}$ is the cost of one hour of product quality verification, including amortization and energy consumption, being electrical or any other nature: C_S are supplementary costs for maintaining and maintenance of the device used [9].

The costs presented in relation (1) can be determined with:

$$C_{pi} = C_p + C_{ex} + C_{set}, \text{ in Euro.} \tag{2}$$

Costs of computerized design for the quality verification equipment it is determined with the relation:

$$C_p = (C_{uc} + C_{usb} + C_{usdc} + C_{usds}) \times t_p, \text{ in Euro/piece,} \tag{3}$$

where C_{uc} is the cost for computer utilization, in Euro/min; C_{usb} is the cost for using the base software, in Euro/min; C_{usdc} is the cost of using the dedicated software, for example AutoCAD, in Euro/min; C_{usds} is the cost for using specialized software, in Euro/min; t_p is the time necessary to design the equipment.

The terms from relation (3) are determined using the next calculation relations:

$$C_{uc} = \frac{P_{ac} + C_{sup.c}}{n_{ac} \times 134400} + S_{pr} + C_{en}, \text{ in Euro/min} \tag{4}$$

In previous relation P_{ac} is the computer price, in Euro; $C_{sup.c}$ are the additional costs: maintenance, service, upgrade for the computer (15% from P_{ac}), in Euro; n_{ac} are the numbers of years declared for amortization (3-5 years); S_{pr} is the designer salary, Euro/min; C_{en} energy consumption used for the computer utilization, in Euro/min.

$$C_{usb} = \frac{P_{asb} + C_{sup.sb}}{n_{asb} \times 134400}, \text{ in Euro/min} \tag{5}$$

where P_{asb} is the purchase price for the base software, in Euro; $C_{sup.sb}$ are additional costs to maintain and upgrade the base software (10% from P_{asb}), in Euro; n_{asb} are the number of years in which the product will be amortized [10].

$$C_{usdc} = \frac{P_{asdc} + C_{sup.sdc}}{n_{asdc} \times 134400}, \text{ in Euro/min} \tag{6}$$

In relation (6) P_{asdc} is the purchase price for the dedicated software; $C_{sup.sdc}$ are additional costs used for maintenance and upgrade (10% from P_{asdc}); n_{asdc} are the number of years in which the product will be amortized.

$$C_{usds} = \frac{P_{asds} + C_{sup.sds}}{k \times n_{asds} \times 134400}, \text{ in Euro/min} \tag{7}$$

In previous relation P_{asds} is the purchase price for the specialized design software, in Euro; $C_{sup.sds}$ are additional costs used for maintenance and upgrade (10% from P_{asds}); k is the coefficient of how much the software will be used in year ($0 \le k \le 1$); n_{asds} are the number of years in which the product will be amortized.

In relations (3-7) was considered the equipment is used eight hours every day.

Executions costs (manufacturing costs), C_{ex}, of the devices, are calculated with next relation [3]:

$$C_{ex} = C_M + S + R, \text{ in Euro} \tag{8}$$

C_M is the cost for the materials used in the manufacturing of the device, determined with relation:

$$C_M = \sum m_S - \sum c_1 \times k(m_S - m_{p)}, \text{ in Euro} \tag{9}$$

In previous relation C_M is the cost of one kg of material, in Euro; m_S is the mass of the semi-manufactured parts used for production of the measurement or control device, in kg; c_1 is the cost of one kg of recovered waste (reused), in Euro/kg; k = 0.8 – waste recover coefficient; m_p mass of finite device.

Cost from remuneration offered to direct productive operators are calculated with relation:

$$S = \sum_{i=1}^{n} N_{t_i} \times \delta_i, \text{ in Euro} \tag{10}$$

In relation (10) N_{ti} are the manufacturing (machining, measuring/control, assembly, final assembly) time norms, in hours, necessary to produce one product; δ_i hourly salary, in Euro/hour, used for each operation necessary; n number of operations used necessary.

Cost for the production facility, R, are determined proportional with the payments for the direct productive operators, maybe also other influence factors [5]:

$$R = \frac{C_R}{100} \times S, \text{ in Euro} \tag{11}$$

C_R is the percentage of general costs imposed by the manufacturer.

$N_{t/v}$ is the time norm for the product quality verification operation (calculated or measured).

$C_{o.ech}$ is the cost of one hour of working for the devices, including amortization, energy consumption cost (electrical or any other energy used); C_S are additional costs for maintenance of the equipment used.

For both variants used for product quality inspection, it can be written next relation by attaching these two indexes, u (ultrasounds) and l (liquids) [8].

$$C_{vu} = C_{piu} + n_p \left(N_{\frac{t}{v}u} \times C_{o.echu} + C_{Su}\right) \tag{12}$$

$$C_{vl} = C_{pil} + n_p \left(N_{\frac{t}{v}l} \times C_{o.echl} + C_{Sl}\right) \tag{13}$$

By equivalence both relations (12) and (13), it can be obtained the critical number of pieces for which the cost of product quality inspection, $n_{p.cr}$, is equal for both ultrasounds and penetrant liquids operations [6].

$$n_{p.cr} = \frac{C_{pil} - C_{piu}}{\left(N_{\frac{t}{v}l} C_{o.echl} + C_{Sl}\right) - \left(N_{\frac{t}{v}u} C_{o.echu} + C_{Su}\right)} \tag{14}$$

For simplification is noted:

$$N_{\frac{t}{v}u} C_{o.echu} + C_{Su} = C_u \tag{15}$$

$$N_{\frac{t}{v}l} C_{o.echl} + C_{Sl} = C_l \tag{16}$$

and results

$$n_{p.cr} = \frac{C_{pl} - C_{piu}}{(C_l) - (C_u)} \tag{17}$$

C_u and C_l are costs for product quality inspection by ultrasounds or penetrant liquids.

Each cost from general relation (17) can have bigger values or smaller values one compared to the other, depending on each condition. Therefore, it can be found four cases, presented in Figures 1 ... 4.

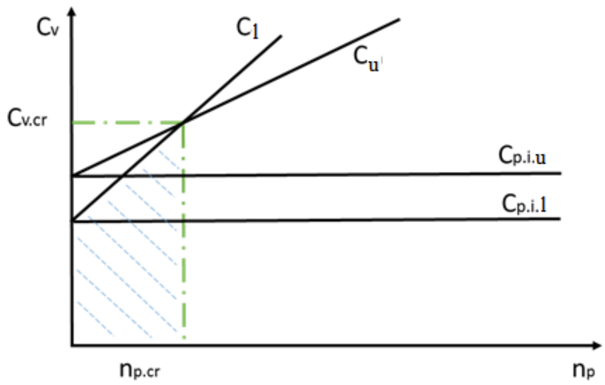

Fig. 1. Variation of product quality verification costs by number of pieces, when $C_{piu} > C_{pil}$; $C_l > C_u$

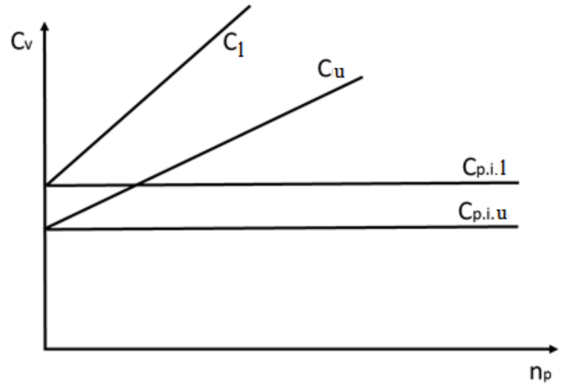

Fig. 2. Variation of product quality verification costs by number of pieces, when $C_{pil} > C_{piu}$; $C_l > C_u$

From graphs representation of these four possible cases, it can be determined the utilization of economical domain for the two variants used for product inspection: ultrasounds or penetrant liquid [7]:

If $C_{pim} > C_{pic}$; $C_c > C_m$, minimal verification cost it is obtained by penetrant liquid if np is from 1 to n_{pcr}.

If $C_{pic} > C_{pim}$; $C_c > C_m$ minimal verification cost is obtained by ultrasounds method no matter how many pieces are verified.

If $C_{pim} > C_{pic}$; $C_m > C_c$, no matter the number of pieces, penetrant liquid method is always the most cost effective.

If $C_{pic} > C_{pim}$; $C_m > C_c$, minimal verification cost is obtained with penetrant liquid method, if $n_p > n_{cr}$.

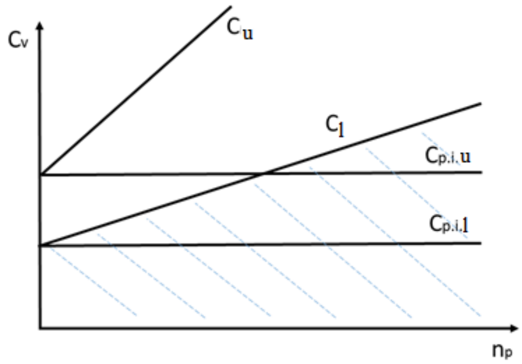

Fig. 3. Variation of product quality verification costs by number of pieces, when $C_{piu} > C_{pil}$; $C_u > C_l$

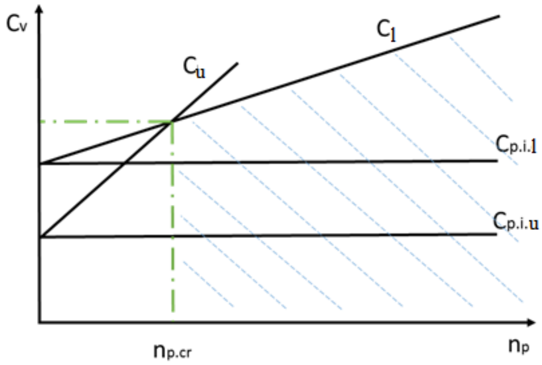

Fig. 4. Variation of product quality verification costs by number of pieces, when $C_{pil} > C_{pim}$; $C_u > C_l$

3. Calculations performed to determine which method is most cost effective

Inspection methods of machined pieces are methods based on ferromagnetism, penetrant radiation, acoustic and ultra-acoustic emission, capacity, allow the visualization of surface or depth microstructural defects, which can have a negative influence over the next technological process, like for example assembly. With structural magnetism and the method with penetrant liquids.

For the case study below two from the above method where chosen, the ultrasounds method and the method with penetrant liquids, which are the most common found and suitable for the machining process.

The ultrasounds are elastic oscillations with high frequency of 16 kHz, sometimes reaching 13×10^8 Hz and the surface or depth defects the frequency can reach 1 MHz. The waves have the property to propagate, refract and diffuse in a different way depending on the environment though which they are travelling. If defects are existing in the body of the products, will modify the intensity and the length λ of the ultrasounds, which are travelling though that material, like in Figure 5.

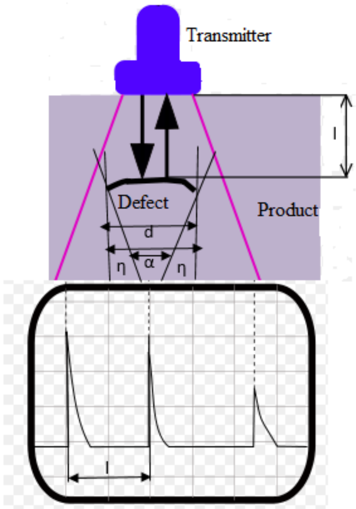

Fig. 5. Ultrasounds verification of an internal defect [1]

Where the diffraction angle can be calculated with:

$$\sin(\eta) = 1.22\frac{\lambda}{\alpha} \tag{18}$$

and the dimension α of the dissipated shadow at a distance *l* from the defect can be calculated with:

$$\alpha = d - 2l \times tg(\eta) = d - 2.44\frac{l \times \lambda}{\sqrt{d^2 - 1.49\lambda^2}} \tag{19}$$

in this way, the defect dimension can be calculated with evidence of the ultrasounds dissipation α.

At the base of the inspection method with penetrant liquids it can be found a capillary entering phenomena of liquid with high filling properties, which will penetrate in the surface defects or in the interior of the product, when this communicates with the surface of piece. This method applies for non-magnetic materials, pieces that must have a long-life, welded, cast or moulded. The operations needed to perform such an inspection are detailed in Figure 6 and they are described like this:

a. the surface is covered with a penetrant liquid, LP, which will penetrate all surface defects;
b. the penetrant liquid excess is removed with water jet;
c. on the clean surface is then applied a developer, DV, a substance with a high power of absorption;
d. the defects can be highlighted with UV lights if the penetrant is fluorescent or
e. the defect can be highlighted by the colour, if the penetrant liquid is coloured.

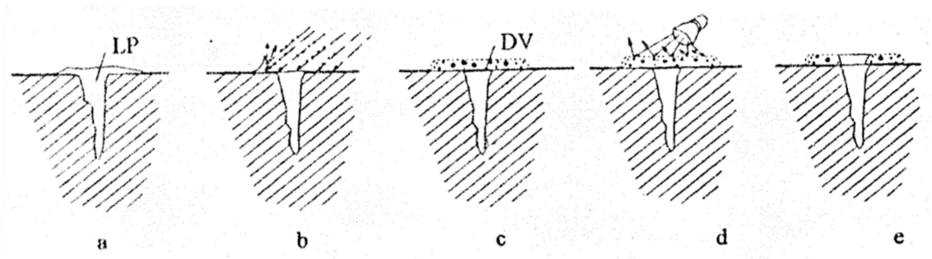

Fig. 6. Penetrant liquid verification steps of a surface defect [1]

For exemplification, are presented next calculations, for the product presented in Figure 7, where must be decided which inspection variant is more efficient: the ultrasounds method or the penetrant liquid method. The calculations took in consideration various variables presented in this paper, which can be found in Table 1.

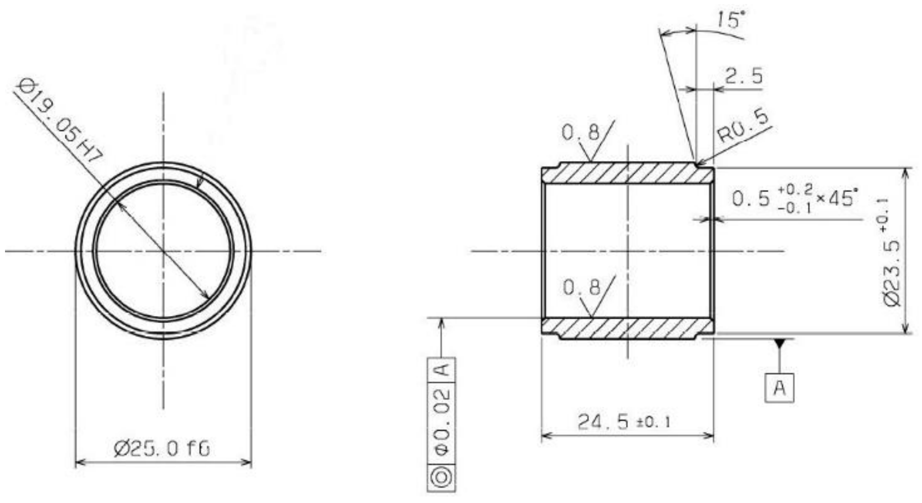

Fig. 7. Technical drawing of the product that needs to be inspected

Taking all these variables in consideration in Figure 8 are presented the results for each inspection method and in Table 2 the results calculated for each cost.

Table 1. Variables used in the calculations

Computer [Euro]	Cost one kWh [Euro/kWh]	Energy/day [Euro]	Designer salary [Euro/min]	IT salary [Euro/min]	3D modelling [min]	Windows [Euro/min]	AutoCad [Euro/min]
9000	0.060	0.432	0.310	0.410	20	1.00	1.00
Additional cost for computer [Euro]	Additional cost for software [Euro]	Computer amortization [years]	Windows amortization [year]	AutoCad amortization [years]	Special software amortization [years]	Profit of the company who is making the special software (%)	
5142	200	5	1	5	2	15	

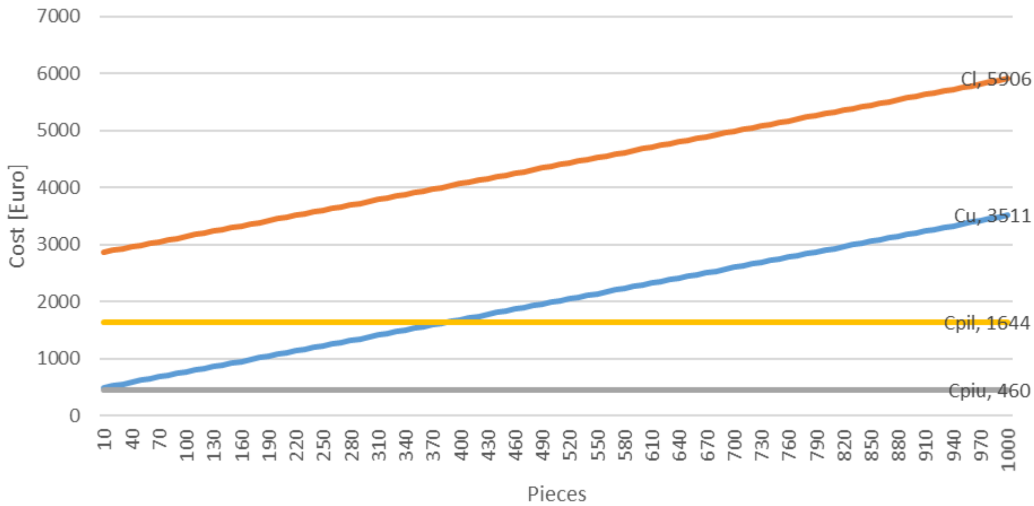

Fig. 8. Variation of product quality verification costs by number of pieces, when $C_{pil} > C_{piu}$; $C_l > C_u$

Table 2. Calculations for the costs presented above

Name of the cost	Cost in Euro
$C_{o.echu}$	14.38
$C_{o.echl}$	35.69
C_{piu}	466.8046
C_{pil}	2834.3246
C_{su}	3.03
C_{sl}	3
$N_{t/vu}$	0.001
$N_{t/vl}$	0.002

By plotting the results, it can be found that even if the time for verification is almost the same in both cases, maintenance costs are almost equal, the best product quality inspection for surface and depth defects is with penetrant liquids, no matter the volume of pieces that needs inspected.

4. Conclusions

Taking in consideration all presented in this paper, it can come off next conclusions and recommendations:

1. The cost for the equipment and method used for product quality inspection must be justified and balanced by the precision and productivity of them.
2. The device and method complexity for product quality inspection takes in consideration: productivity, verification cost, but also the qualifications needed by the quality inspector: a higher

complexity could mean a simple method and an increased productivity which doesn't necessarily mean a higher qualification for the quality inspector, instead a higher complexity and method means for the quality inspector a higher qualification, which is only justified by a very big productivity.

3. Calculations also indicates that the process needs to produce at least 10,000 pieces in order to absorb the initial purchased price and initial setup costs, no matter what option it is chosen. Depending on the application used, for serial production of less than 10,000 pieces it can be suggested that other solutions are found.

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