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Analysis of the Level of Efficiency of Control Methods in the Context of Energy Intensity

Andrzej Pacana [1,*], Karolina Czerwińska [1] and Grzegorz Ostasz [2]

[1] Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland
[2] Faculty of Management, Rzeszow University of Technology, al. Powstancow Warszawy 12, 35-959 Rzeszow, Poland
* Correspondence: app@prz.edu.pl

Abstract: In enterprises, the management of detection methods usually refers to ensuring the identification of nonconformities. This management is incomplete and incompatible with the concept of sustainability (it ignores electricity consumption and costs). To date, no models have been developed to support the analysis of detection methods in terms of the relationship of efficiency–energy consumption. The purpose of the study was to develop proprietary software to analyse the level of efficiency of detection methods for casting products in the context of their energy intensity. The model supports effective management of the quality control process, optimising the relationship of product quality–energy intensity of the process. The model integrally combines detection methods, so it was possible to identify critical product nonconformities and analyse these methods to determine their effectiveness, time efficiency, cost efficiency, and energy intensity. As a result of the implications of the software, a ranking of the total efficiency of electrical connector detection methods was obtained. The numerical values of the total efficiency index indicated that X-ray testing was the most effective, well ahead of the other methods. The eddy current and ultrasonic tests show similar values for the index analysed. A verification of the software was carried out that confirmed its suitability in foundry enterprises.

Keywords: energy intensity; checkpoint; Industry 4.0

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1. Introduction

It is now becoming much more economical to use energy rationally than to create new generation capacity [1], which is increasingly based on imperfect technologies [2]. It was decided that in the context of energy intensity, the modern economy pays special attention to reasonable energy consumption while maximising the overall economic effect of production companies [3], which translates into a global effect [4]. The authors [5–7] point out that this issue is all the more important because energy intensity should be a central instrument that contributes to the creation of sustainable development.

In the area of the topic raised, the issue of the energy intensity of the economy as a whole is widely discussed [8–10]. However, by narrowing the issue in the literature, there is also a considerable amount of analysis of the energy intensity of individual sectors of the economy [11]. This means that the level of energy consumption is most often characterised by categories such as total, global, and sectoral direct consumption [12]. It should be noted that “total consumption” (as well as global consumption) refers to secondary and primary energy sources, as a result of which the part of energy contained in primary carriers and then transformed into secondary carriers is included twice within the measure under study [13]. From the perspective of energy balance, this is of little importance, but such doubling of energy can distort the result of analyses in a situation where it is the starting element for calculating energy intensity measures [14]. To avoid skewing the values obtained, it is possible to use energy intensity measures that focus only on primary carriers [15]. In the literature and economic studies, the most common measures of energy intensity are those related to the entire economy, which are based on GDP (gross domestic product). This allows us to determine the average level of energy intensity of the economy [16]. At the same time, the intensity of the energy within individual sectors or industries of the economy varies considerably. As a result, even seemingly small changes in the area of some sectors can affect changes in the average energy intensity, while the impact of others (even in the case of significant changes) can be practically imperceptible [17]. The impact is not so much the level of intensity of sectoral energy, but the shares of individual sectors in total production [18]. Having data indicating the value added of specific sectors or data on energy inputs and production globally, it is possible to determine and perform analyses of their energy intensity [19].

Taking into account the energy intensity of economies in many studies, the authors have drawn attention to the manufacturing sector, within which the level of energy consumption is the highest [20]. Due to this, it is common belief that the supervision of energy flow paths in a manufacturing enterprise is an important issue in terms of its efficient and rational use. Work is being carried out to develop models used to predict electrical energy production and consumption in manufacturing sectors based on, for example, fuzzy logic [21], the Holt–Winters forecasting model [22], the time series model (autoregressive model) [23], night light images, and artificial neural networks [24].

Today, progressive automation and increased development of IT services and technology have extended their reach to virtually all areas of human life [25,26]. Competitive pressures accompanying globalisation, as well as the progressive modernisation of technologies and the resulting disruption of functioning business models, contribute to the cheaper, more immediate, and more radical implementation of various types of innovation [27]. Often, well-established manufacturing plants involve the latest technologies outside of their core business to increase the level of modernisation and innovation of the company [28]. Increasingly, technologies considered sustainable characteristics are becoming a distinguishing attribute for innovative investments [29], and their rapid identification determines significant potential, becoming the so-called critical success factor [30].

Currently, a key element within each industrial field is casting, in relation to which, as in relation to technology, more and more requirements are imposed [31]. Production of products in casting technology while maintaining the expected level of their quality is associated with the supervision of several technological parameters that affect the quality of the final product [32]. The main difficulty associated with casting and subsequent manufacturing processes is the significant degree of restrictions on the simultaneous control of all factors associated with the technological process [33]. Therefore, due to the casting technology and machining processes used, there is a significant risk of defects in the structure of the material [34]. Scientific studies have pointed out that, in particular, incompatibility of porosity-type materials has a negative impact on the strength, fatigue properties [35], and ductility of the product [36]. Since a significant amount of fatigue damage begins on the surface of the products, surface roughness is a factor that has a significant impact on the fatigue strength properties of the castings [37,38]. However, structural defects, i.e., oxide membranes, porosity, or inclusions located close to the surface, show the crack-initiating effect of the material. Elimination of such critical incompatibilities is the subject of much research [39,40].

Demonstrating that a cast product has no defects is the most important factor in demonstrating the high quality and competitiveness of a product [41]. Thanks to the use of casting technologies, it is possible to produce products characterised by complex construction, which are often components of measuring instruments, equipment, machinery, and vehicles [42]. Given the ever-increasing development of design complexity and the closely related increase in the requirements for the components used, it is necessary to perform both material and technical detection [43,44]. Regarding ensuring the appropriate level of quality of the offered products, an important issue is not only the appropriate selection of production parameters, but also the selection of methods to detect inconsistencies in the product [45].

In terms of product nonconformity detection methods used in the quality control of aluminium castings, non-destructive testing (NDT) is the most energy intensive and yet the most effective type of detection [46]. This type of testing makes it possible to identify nonconformities without affecting the surface and structural features of the tested product. The primary goal of implementing NDT is to detect and evaluate discrepancies in the form of material discontinuities [47]. However, in the field of inspection of complex geometry, and in this case increasing the uncertainty of detection, it is recommended to combine different NDT methods in the inspection cycle [48]. This creates a situation in which an increase in the quality of the detection process is closely associated with an increase in the intensity of the inspection process energy [49].

Analyses of the efficiency of the control process should take into account not only the level of identification of nonconformities itself, but also the degree of energy consumption of the process. Today, energy efficiency is one of the most important management issues in modern manufacturing enterprises [50]. In general, energy efficiency is defined as the value of the result obtained, service rendered, and product produced compared to the energy expenditure incurred. It provides a measure of the efficiency of energy use in economic activities [51]. According to sources, energy efficiency is a key factor in the innovation and development of manufacturing companies. The tendency to minimise energy losses has become a widely desired measure of sustainable development. At the same time, the development of manufacturing companies is not necessarily understood as an increase in the consumption of energy resources [52]. The dissonance between capacity expansion and the level of energy consumption has a permanent character due to energy saving trends in technology upgrading and innovation policies [53].

According to many authors, the intensity of energy should be central to the optimisation of manufacturing processes, both in the production process and in the associated quality control process [54]. Energy, which is both a factor of production and an element of final consumption, does not have substitutes and therefore can have a significant impact on the choice of the detection method and its frequency [55]. Although final energy consumption is a simple derivative of its purchase by the operator, the diagnosis itself and subsequent analysis, active energy management, and optimisation decisions require data for areas of potential energy savings [56].

In any industrial enterprise, electricity consumption is one of the largest operating costs. In the context of ever-increasing energy prices, taking measures to optimise consumption levels becomes more important than ever [57]. Progress in energy efficiency has a positive impact on reducing operating costs, energy intensity, increasing the reliability of equipment reliability, and production efficiency [58]. Improvements in the level of energy intensity should be sought not only in relation to processes with high energy consumption, but also in relation to all other processes carried out in the enterprise looking for savings [59]. Increasing energy efficiency contributes to reducing the environmental impact of production activities. Furthermore, it supports the level of resilience of the organisation to fluctuations in energy prices, which, as a result, increases the level of competitiveness in the market [60].

Analysis of the literature on energy intensity and reduction of energy consumption costs of individual manufacturing enterprises indicates that efforts are being made to create optimisation methods. Table 1 shows the main applications of energy management methods in enterprises.

Table 1. Characteristics of the methods used to manage energy intensity.

Author of the Study	Method	Application	Brief Description of the Method	Model Verification
Olaru, LM.; Gellert, A.; Fiore, U.; Palmieri, F. [21]	A method based on based on fuzzy logic	Modelling of electricity production and consumption	An intelligent energy management system that can make decisions and adjust consumption according to the current context and future electricity levels.	Evaluations of the method were carried out on a data set collected in a real household
Matos, C.; Sola, AVH.; Matias, GD.; Lermen, FH.; Ribeiro, JLD.; Siqueira, HV. [22]	A method based on the Holt–Winters predictive model	Energy Demand Planning in the production processes of enterprises	The model integrates costs with electricity consumption and power demand in aggregate production planning, taking into account market uncertainty.	The model was empirically applied to the food industry, considering a family of potato chips.
Lakovic, M.; Pavlovic, I.; Banjac, M.; Jovic, M.; Mancic, M. [23]	Method based on time series model (autoregressive model—AR)	Electricity consumption forecasts	The model uses a Monte Carlo simulation method to predict and analyse changes in energy consumption. One of the main parts of the AR model is a seasonal pattern that takes into account the climatic conditions for a given geographic area. This part of the model was determined by the Fourier transform and was used to avoid model complexity. A probabilistic range of input values is used to determine the future probabilistic level of energy consumption.	The model was verified using data from a tobacco plant as an example.
Jasiński, T. [24]	Method based on night light images and artificial neural networks	A model used to predict electricity production and consumption in the manufacturing sectors.	The SSN input variables were based on night-time light images from VIIRS DNB. The use of SSN enabled modelling of nonlinear relationships related to the complex structure of electricity demand. Satellite data were collected for 2013–2016 and included images of better quality (including higher resolution). The images were used to create multilayer perceptron models. The results obtained using the SSN method were compared with those obtained using linear regressions.	The survey covered the area of Poland
Grigoras, G.; Neagu, BC.; Iwanow. O. [25]	Method based on production scheduling in small and medium-sized enterprises	Model used to flatten consumption profile, save energy, and improve energy efficiency and economic performance	An effective approach to flattening the electricity consumption profile based on production scheduling in small and medium-sized enterprises.	Approach tested on an industrial customer (small car repair company)

Compared to the characterised methods for managing energy consumption in enterprises (presented in Table 1), the developed data analysis model is distinguished by the following features:

- method based on indicator analysis;
- application in the area of quality control of a manufacturing enterprise;
- multifaceted analysis (capturing the effectiveness of the method of nonconformity detection, cost, and time of unit detection and energy intensity of detection methods);

- identification of relationships occurring between quantities key to quality control management (effectiveness of nonconformity detection method, cost and time per unit detection, and energy intensity of detection methods);
- verification of the model in one of the foundry companies;
- development of proprietary software CmEfficiencyNew version 1.1.5 based on the assumptions of the model;
- quick turnaround time of the analysis;
- generation of a summary analysis report;
- the possibility of adapting CmEfficiencyNew software to online operation (correlation of software with automated quality control).

The methods presented in Table 1 either apply to the enterprise (treating it as a whole) or concern only production processes. However, according to the idea of continuous improvement of manufacturing enterprises, it is necessary to optimise not only the production process itself but also the quality control process that is integrally connected with it. Unlike the methods presented, the developed model allows for the realisation of such analyses. Another important difference between the characterised methods and the developed model is the number of variables that are taken into account during the study. The developed model shows the correlation between the energy intensity of nonconformity detection methods and the level of their efficiency, time, and cost of implementing a single test. Such a multilevel analysis is not allowed by the methods presented in Table 1. Another point indicating the superiority of the developed analysis model over the methods presented in the literature is the fact that the optimisations performed on the basis of the developed model will allow not only to reduce energy consumption and reduce the cost of process execution (as in the case of the methods in Table 1), but also to identify critical product nonconformities and determine the level of efficiency of the nonconformity detection method. The superiority of the proposed model also lies in the ability of the author's CmEfficiencyNew software to be used in any enterprise and the ability to conduct analysis based on a wide range of nonconformity detection methods. The programme includes an extensive library of nonconformity detection methods.

To date, the state of research, especially in information on the measurement of energy intensity of individual processes carried out in manufacturing companies, both retrospectively and prospectively, is unsatisfactory and forces a continuous methodological search. The research problem of the study is to propose an answer to the continuous search for a method of solving the problems of managing the effectiveness of nonconformity detection methods in terms of quality—energy intensity. Due to the increase in automation of detection methods (and the increase in energy consumption in this area), rational management is needed. The research undertaken should take into account the relationship of product quality with the energy consumption of the detection method. Therefore, it is reasonable to create software to support the process of managing detection methods in the context of their effectiveness and energy consumption.

The purpose of the research was to develop a model to analyse the level of efficiency of detection methods for products made of aluminium alloys and, on its basis, to create original software to improve the energy quality management of the quality control process. The developed model contributed to the effective management of the quality control process with an emphasis on optimising the relationship between product quality and energy intensity of the process. An additional goal was to verify the effectiveness of the software in one of the casting plants.

The originality of the method developed on the basis of which CmEfficiencyNew software was created lies in the ability to carry out systematic management of energy intensity in the area of quality control. The original approach to energy management in this area allows the realisation of multifaceted analyses. The innovative model takes into account factors relevant to quality control (the effectiveness of the detection method, the time and cost of detection, and the energy intensity of the detection methods) and allows one to determine the relationship that occurs between them. This approach allows indicating the total level of energy efficiency of nonconformity detection methods and the volume and structure of energy consumption. Based on the parameters of the aforementioned indicator, it is possible to optimise energy quality optimisations as part of the process management improvement. Thus, the model for analysing the efficiency of nonconformity detection methods fills the research gaps identified in the literature.

The study consists of an introduction that includes a description of the research background, a review of the scientific literature, the rationale that prompted the topic, and the purpose of the study, and identifies the elements of originality of the proposed methodology to analyse the level of effectiveness of control methods. The second chapter is devoted to a description of the proposed method for analysing the level of efficiency of control methods and a description of the author's CmEfficiencyNew software. The resulting software was created to improve the implementation of the analysis. The third chapter, "Model verification and results", presents how the validity of the developed model and the performance of the author's software were checked. A step-by-step description of how the various stages of the quality energy analysis of the electrical connector quality control process were carried out. This was conducted in one of the foundry enterprises. In the fourth chapter, the discussion, the topics most often discussed in the literature in the field of energy intensity and ways and methods of measuring electricity demand are discussed. The validity of the research topic is proved, and the significance of the research results obtained is demonstrated. The last chapter of the study indicates the main conclusions and future research directions.

2. A Model for Analysing Control Methods

The constant increase in the complexity of designs and the increasing demands on components and materials require the implementation of technical and materials research [61]. Maintaining the assumed level of quality of manufactured casting products involves implementing mature quality management. Most often, it refers to the performance of quality control, the implementation of production processes, and the monitoring of the correctness and effectiveness of nonconformity detection methods [62]. When talking about the effectiveness of nonconformity detection methods, it is necessary to pay attention to their key features, which include effectiveness of the method, type of nonconformities identified, time and cost of performing a single inspection, and energy intensity of the test.

The proposed model to analyse the level of efficiency of detection methods supports the management of quality and energy of the enterprise. Within the framework of the study, the phrase "detection methods" refers to the detection of nonconformities in cast aluminium alloy products. All checkpoints (X-ray, ultrasound, eddy current, visual, and dimensional inspections) established within the manufacturing process are tested. The model, thanks to the selection of detection methods detecting critical nonconformities, allows for their detailed characterisation and significantly supports the determination of improvement actions against the quality problems occurring. Taking into account the energy intensity of detection methods provides direct information on the level of energy consumed, contributing to rationalisation of its use. This makes it possible to determine the quality–energy correlation of quality control methods that is a priority for the correct development of manufacturing enterprises operating in the era of smart factories and Industry 4.0. The study analyses the level of energy consumption and the energy intensity of casting inconsistency detection methods. The analysis does not include heat generated during the casting process and issues related to electricity.

The model developed to analyse the effectiveness of nonconformity detection methods (Figure 1) takes into account selected nondestructive testing methods due to their widespread use in the foundry industry [63,64], their significant level of effectiveness [65], and the possibility of automating detection [66,67]. Non-destructive tests are used to assess durability [68] and the surface condition of the material under test [69]. These tests include visual inspection, X-ray inspection, ultrasonic inspection, eddy current inspection, and dimensional inspection, which are most often arranged sequentially within the manufacturing process. Based on the information obtained from the quality control, it is possible to indicate the efficiency parameter of the total inspection points. To increase the efficiency of the implementation of the course of action within the framework of the proposed model, the proprietary software CmEfficiencyNew was created. The operation of the programme is based on the assumptions included in the model. Dedicated software allows for automating the analysis of quality control data. It is a flexible and functional solution because it allows maximum use of hardware and human resources. The task of the software is not only to aggregate data and then display them in an easy-to-use graphical way, so that quality officers have real-time access to the most relevant information, but also to continuously indicate the level of effectiveness of detection methods. The flow chart of analysis of the level of efficiency of control methods for aluminium castings, taking into account the correlation occurring between their widely understood efficiency and energy intensity, is shown in Figure 1.

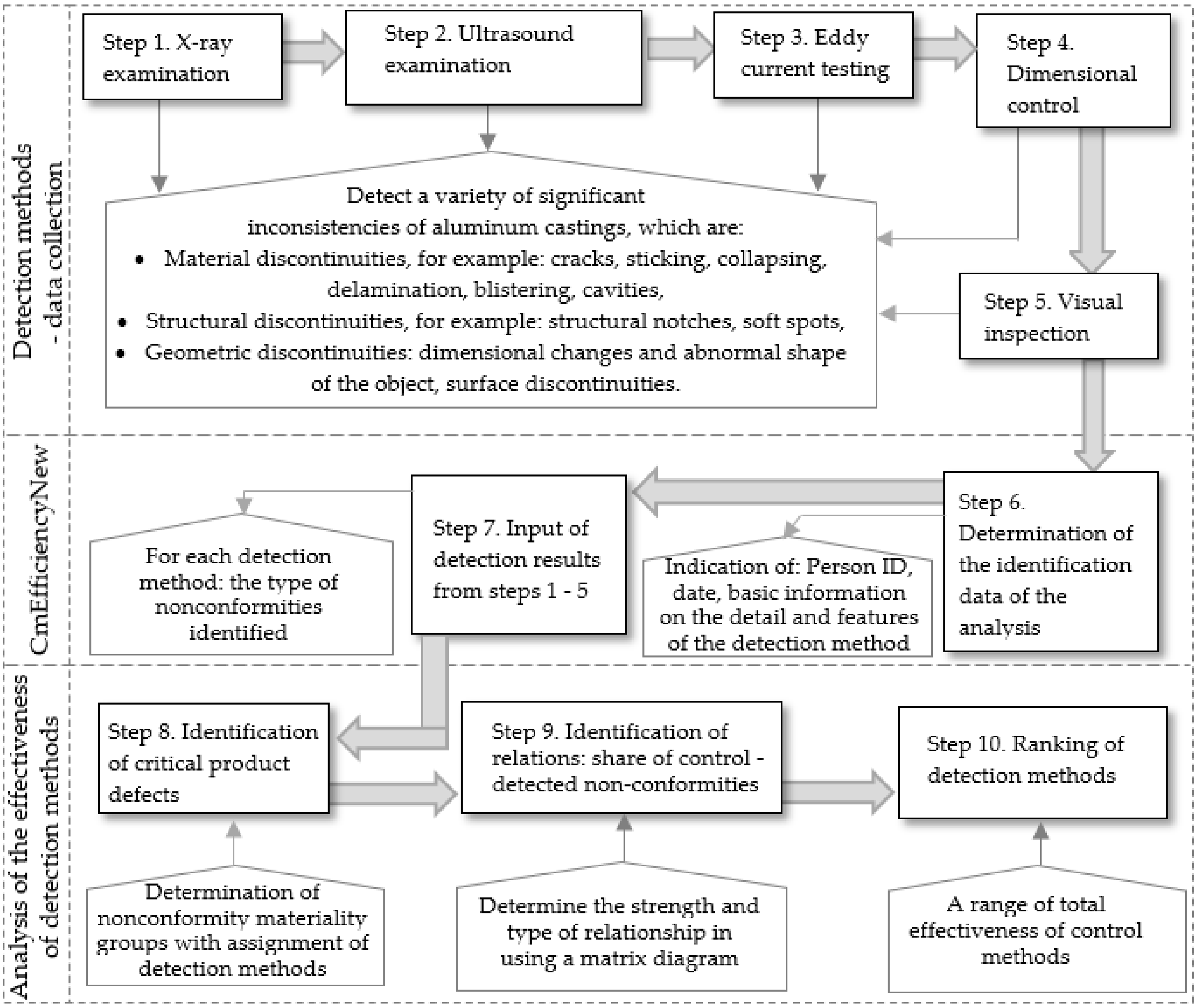

Figure 1. Idea diagram of the control methods analysis model.

In the developed model (Figure 1), three research areas were identified, including detection methods as a means of data collection, the use of proprietary CmEfficiencyNew software, and analysis of the effectiveness of control methods in terms of energy intensity. The use of staged detection of a diagnostic–analytical nature makes it possible to realise activities that go beyond the realm of passive quality control.

2.1. Step 1. X-ray Examination

Detection by radiographic testing (RT) should be carried out in the following main steps [70]:

- introduction of X and γ radiation;
- obtaining an image in the form of a "shadow", in the direction of propagation of radiation;
- registration on radiographic films and computer registration in real-time radiographic systems;
- preparation of a report on the examination of the casting.

X-ray detection allows for the detection of spatial discontinuities, blisters, residual shrinkage cavities, flat discontinuities, shrinkage cracks, and inclusions. In addition, it makes it possible to detect and evaluate changes in the thickness of the walls of castings and their shells. Radiograms show two-dimensional shadow images of three-dimensional discontinuities [71]. The images of discontinuities show the shape of discrepancies and their dimensions (length and width). The difference in the level of blackness of the radiographs, in the area of discontinuity occurrence and in the area without discontinuity, contains information about the height of the discontinuity in the plane parallel to the direction of propagation of radiation [72].

When implementing the survey, it is important to keep in mind the limitations of the method. It is possible to detect internal and surface discontinuities favourably orientated with respect to the direction of radiation propagation. The sensitivity of discontinuity detection is limited to discontinuities of approximately (0.5% $\div$ 2%) of the thickness of the test object, which limits the detection capabilities in the context of the thickness of the workpiece. There is a danger of exposing personnel and the environment to irradiation [73].

2.2. Step 2. Ultrasonic Testing

Ultrasonic testing (UT) is implemented in the following steps [74]:

- introduction of ultrasonic waves (elastic waves) into the object, i.e., mechanical vibrations with frequencies higher than 20 kHz; it is necessary to scan the surface of the object, moving the head along the surface of the object;
- detection of signals (pulses), sent by waves passing through objects;
- development of a casting test report.

UT testing is implemented to identify the most dangerous discontinuities: flat, narrow-gap, and spatial discontinuities, as inconsistencies, as well as internal and surface cracking, inclusions, residual cavities, sticking, lack of remelting, foreign material inclusions, and air bubbles [75]. This type of testing allows for the detection of discontinuities with diameters comparable to or greater than the wavelength. It is also possible to measure the thickness of objects, with one-sided access [76].

The signals analysed during unit detection (mainly amplitude, phase, and spectrum, as well as the envelope of the signals, obtained when the heads are moved around or along the discontinuity) contain information about discontinuities in objects. Ultrasonic wave-induced signals are obtained from the walls of objects and discontinuities present in the castings [77]. The information contained in the passage of ultrasonic waves is used to determine the location (i.e., to determine the distance from the test surface over which the probe is guided) of the walls of objects and discontinuities occurring in the casting. However, to evaluate the dimensions of discontinuous objects, the information contained in the envelope of echo signals for discontinuities, obtained when moving the heads along the discontinuity, is used mainly. A definite limitation of ultrasonic testing is the ability to detect discontinuities favourably orientated with respect to the wave beam. The sensitivity of the test is limited when the surface of objects is rough [78].

2.3. Step 3. Eddy Current Testing

The principle of detecting discontinuities using the eddy current (ET) method involves the following steps [79]:

- placing objects made of electrically conductive materials in the area of influence of a time-varying magnetic field, produced by inductive transducers;
- processing the signals of the transducers, the amplitude and phase of which contain information about the presence of discontinuities in the objects and changes in the composition of the materials and structure of the objects.

This method makes it possible to detect material discontinuities: first of all dangerous discontinuities extending to the surface of objects (semi-finished and finished products); and also surface discontinuities that are flat, narrow-slit, and relatively large, close to the surface (to a depth of several millimetres) [80]. It also makes it possible to make measurements of object dimensions or electrical conductivity [81]. The indicated discontinuities are dangerous in the context of the operation of the product, because they initiate cracks. In addition, the product at the site of discontinuities shows lower strength parameters.

A tangible advantage of conducting ET surveys is the ability to detect high-speed (on-line and off-line) object detection [82]. However, a limitation is that only electrically conductive objects can be detected: metallic and nonferromagnetic metallic and some composite objects [83].

2.4. Step 4. Dimensional Control

Control of the geometric and dimensional parameters of the casting is carried out by checking and measuring certain characteristics of the casting, which are then compared to the required characteristics contained in the design documentation.

2.5. Step 5. Visual Inspection

As part of the visual inspection, ordinary visual inspection (based on employee self-examination) or visual tests are performed [84]. Machines and detection equipment are not used to implement the visual test (the test is not energy-intensive). However, this method of detecting casting inconsistencies is an inseparable part of quality control [85]. Therefore, this type of detection was not omitted from the analysis model developed.

Ordinary visual inspection is usually the evaluation of castings, their distinction, the assessment of shape, and mutual position of parts. No visual examination is required. Visual examination, on the other hand, is surface examination methods and allows detection of the most dangerous discontinuities, which are surface discontinuities, such as flat and narrow cracks. It is possible to detect cracks with a depth of about 0.1 mm, width from about 0.01 mm, and length from about 0.1 mm. The specification of the visual detection plan is determined by the execution of the test [86]:

- Direct visual testing makes it possible to examine the casting surfaces directly accessible. Inspection is carried out with the naked eye or with the help of magnifying glasses (with magnifications up to 20×) or microscopes.
- Indirect visual examinations are optical examinations that allow examination of surfaces that are not directly accessible for visual inspection. These examinations are carried out using a set of mirrors, endoscopes, periscopes, or videoscopes.

Identified discontinuities are classified by determining the number, type, severity, size, and, finally, their designation [87]. During visual inspection, documentation must be prepared describing test results per unit [88].

2.6. Step 6. Determination of the Identification Data of the Analysis

When analysing the efficiency of detection methods using the CmEfficiencyNew software, it is necessary to enter information by which the study can be identified. In the “Ranking identification” window, one needs to enter the identification number of the employee, the date of the analysis, and the basic information about the workpiece that is subject to quality control. In the next step, in the "Select Control Methods" window, select the detection methods to be analysed and indicate their characteristic parameters.

2.7. Step 7. Input of Detection Results from Steps 1–5

The next step of the analysis is the loading of data from the implementation of quality control using appropriate detection methods. The data refer to the types of identified nonconformities in the tested casting. The data can be imported, for example, from an Excel file.

2.8. Step 8. Identification of Critical Product Defects

In the first step, there is an order of the resultant data from the quality control performed by the methods considered in the model. The following data should be extracted: the name of the identified product nonconformity, the percentage of the specified type of nonconformity, and the cumulative value of the specified type of nonconformity. On this basis, nonconformities are categorised (with particular attention to the frequency of traceability) into three groups:

- group A—critical nonconformities;
- group B—nonconformities that are significant;
- group C—nonconformities of lesser importance.

The identified three groups of nonconformities are subject to visualisation using a Pareto–Lorenz diagram. This procedure makes it possible to establish a range of importance of nonconformities with a significant impact on the emergence of quality problems [89]. This is according to the principle that in each system there is a relatively small number of causes characterised by the greatest influence on the quality of the range of products, while the influence of other factors is small or negligible [90]. The tool used indicates the priorities that are subject to analysis in the subsequent stages of the study.

2.9. Step 9. Identification of the Relationship: Share of Control—Detected Nonconformities

Identification of the type and strength of the relationship between control methods and detected nonconformities is carried out using a matrix diagram. In the area of the diagram, four boxes are distinguished to indicate the correlation that occurs:

- in the first step between the frequency of nonconformity identification and the frequency of detection methods, understood in subsequent steps as the effectiveness of the control method;
- in the second step between the effectiveness of the control method and the unit cost of detection;
- in step three between the effectiveness of the control method and the unit detection time;
- in step four between the effectiveness of the control method and the intensity of detection.

The strength of the relationship is determined to be strong, medium, or weak. These indications provide the data necessary to determine the level of effectiveness of control methods in the context of the energy intensity.

2.10. Step 10. Ranking of Detection Methods

The purpose of the stage is to rank the detection methods in order from the most effective to the least effective methods in terms of the unit detection characteristics studied. Therefore, the principle of "the more, the better" will apply here. This means that the desired result is to obtain a value of 100% within the indicator analysed.

Based on the identified strength of the relationship that occurs between the variables indicated in Stage 7, it is possible to determine the series of efficiency of the detection methods under study. To determine the level of importance of each method, use the formulae in Table 2.

Table 2. Formulae needed to develop methods' validity series.

Name	Model	Designation
Effectiveness of detection methods	$S = CN \cdot (1 - F)$ (1)	S—checkpoint efficiency [%]; CN—frequency of detection of nonconformities [%]; F—frequency of occurrence of the control method [%].
Cost-effectiveness of detection methods	$EK = S \cdot (1 - K)$ (2)	EK—checkpoint cost-effectiveness [%]; S—checkpoint efficiency [%]; K—unit detection cost [%].
Time efficiency of detection methods	$EC = S \cdot (1 - Cz)$ (3)	EC—checkpoint time efficiency [%]; S—checkpoint efficiency [%]; Cz—unit detection time [%].
Energy efficiency of detection methods	$EE = S \cdot (1 - En)$ (4)	EE—energy efficiency of the checkpoint [%]; S—checkpoint efficiency [%]; En—energy intensity of the unit detection [%].
Total efficiency of checkpoints	$E = S \cdot K \cdot Cz \cdot En$ (5)	E—total efficiency [%]; S—checkpoint efficiency [%]; K—cost of unit detection [%]; Cz—completion time of unit detection [%]; En—energy intensity of the unit detection [%].

In the practice of implementing the analysis of the effectiveness of detection methods, the standardisation of the levels of aggregation and details of classification of the data on the specifics of the implementation of detection plays an important role. For this reason, the values indicated in Table 2 are specified in percentage terms.

The values obtained from the individual checkpoints are placed within the relevant parts of the matrix diagrams. With regard to the areas of the diagrams in each of the studied aspects, the aim is to obtain a relationship located in the second quadrant.

The developed model for analysing the effectiveness of inspection methods in the context of their energy intensity takes into account the complementarity of nondestructive testing methods and broad qualitative and cost analyses to build effective systems with a reasonable level of energy intensity. The synergistic model contributes to reducing the degree of uncertainty in the measurement through the gradual implementation of detection tests and rational management of the energy intensity of the quality control process.

3. Model Verification and Results

The test of the presented analytical model was carried out using proprietary CmEfficiencyNew software, whose operation is based on the assumptions made in the model. The CmEfficiencyNew software contributes to effective optimisation of work, continuous monitoring, and management of the quality of preferred products, as well as the energy intensity and cost of detection.

The basis for the analysis presented here is the following materials:

- secondary, which included: literature on the subject, documentation on the production process, and quality control;
- primary, which included interviews with company representatives.

To verify the method, data from Q1 and Q2 of 2022 were used.

A sensitive production process (in terms of quality and energy intensity) was carried out in a manufacturing company located in the southern part of Poland for the study. The selected process produces electrical connectors. An illustrative model of the product is shown in Figure 2.

Figure 2. Electrical connector model.

The electrical connector (a model of which is shown in Figure 2) is made of AlSi7Mg alloy. The finished product, measuring 500 × 100 × 200, weighs 8 kg.

In the context of the use of the built-in functionalities of the CmEfficiencyNew software, there is a "Ranking identification" window (Figure 3), in which it is necessary to specify the employee identification number, date, and basic data about the analysed product.

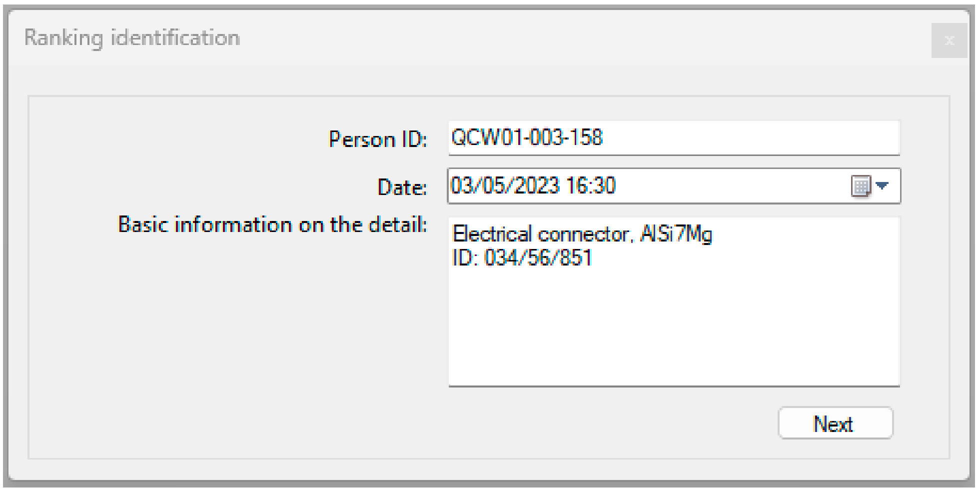

Figure 3. Prepare assumptions for the analysis of the energy intensity of detection methods used within the process under study.

In the dialogue box "Select control methods" (Figure 4), select from a handy library of detection methods used in the case under analysis and indicate historical data on the frequency, cost, time, and intensity of the detection method per unit of detection.

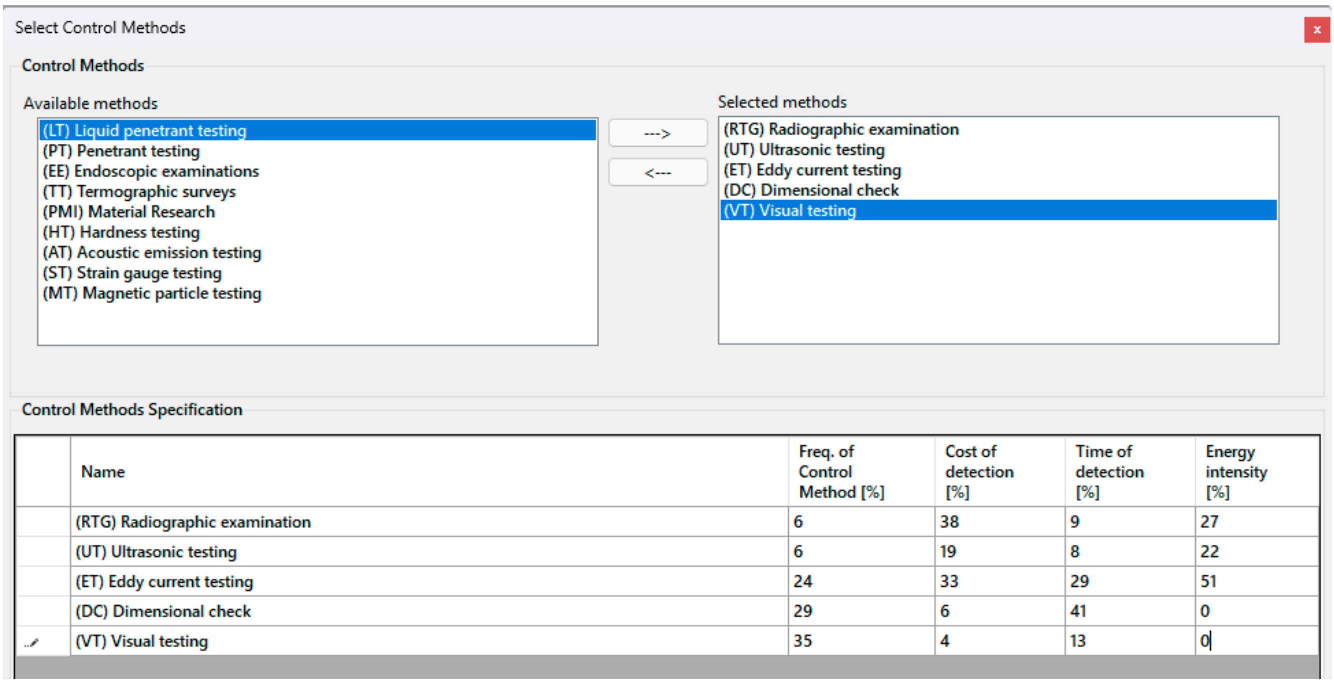

Figure 4. Define the basic parameters that characterise the detection methods implemented as part of the process.

The next step of the analysis after determining the key parameters of the detection methods is to load the quality control. Data on the nonconformities that were identified on the electrical connector during the study period can be imported, for example, from an Excel file. Nonconformities of electrical connectors are ordered in descending order (in terms of frequency of their identification). This step aims to select the most serious defects and critical nonconformities, and to identify the relationship between each type of nonconformity and the inspection method (Figure 5).

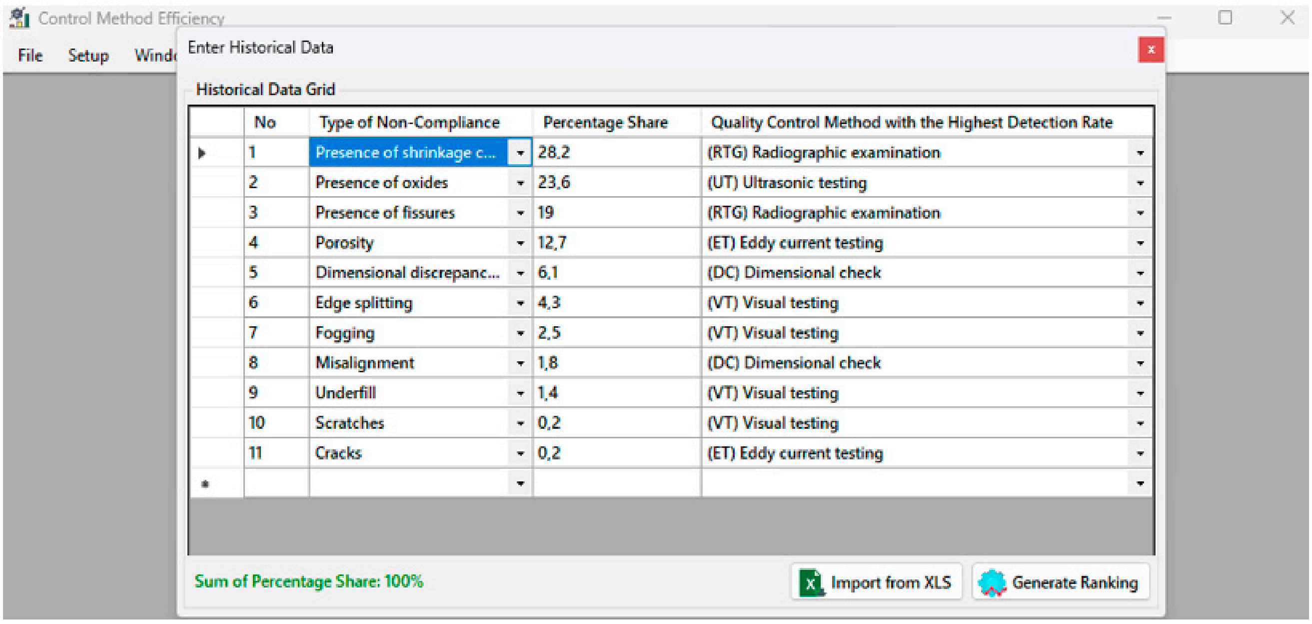

Figure 5. Identification of the 11 most commonly identified inconsistencies in electrical connector casting.

Based on the data entered, the programme generated a report on the analysis of the level of efficiency of detection methods in the context of their energy intensity. The report generated by the programme contains basic information on the implementation of the analysis. Based on the data describing the results of the quality control of the electrical connector, the programme creates a Pareto–Lorenz diagram taking into account the principles of division of nonconformities applicable in the ABC method. This step of the analysis makes it possible to divide nonconformities into three groups: critical, relevant, and less relevant. The first part of the report is shown in Figure 6.

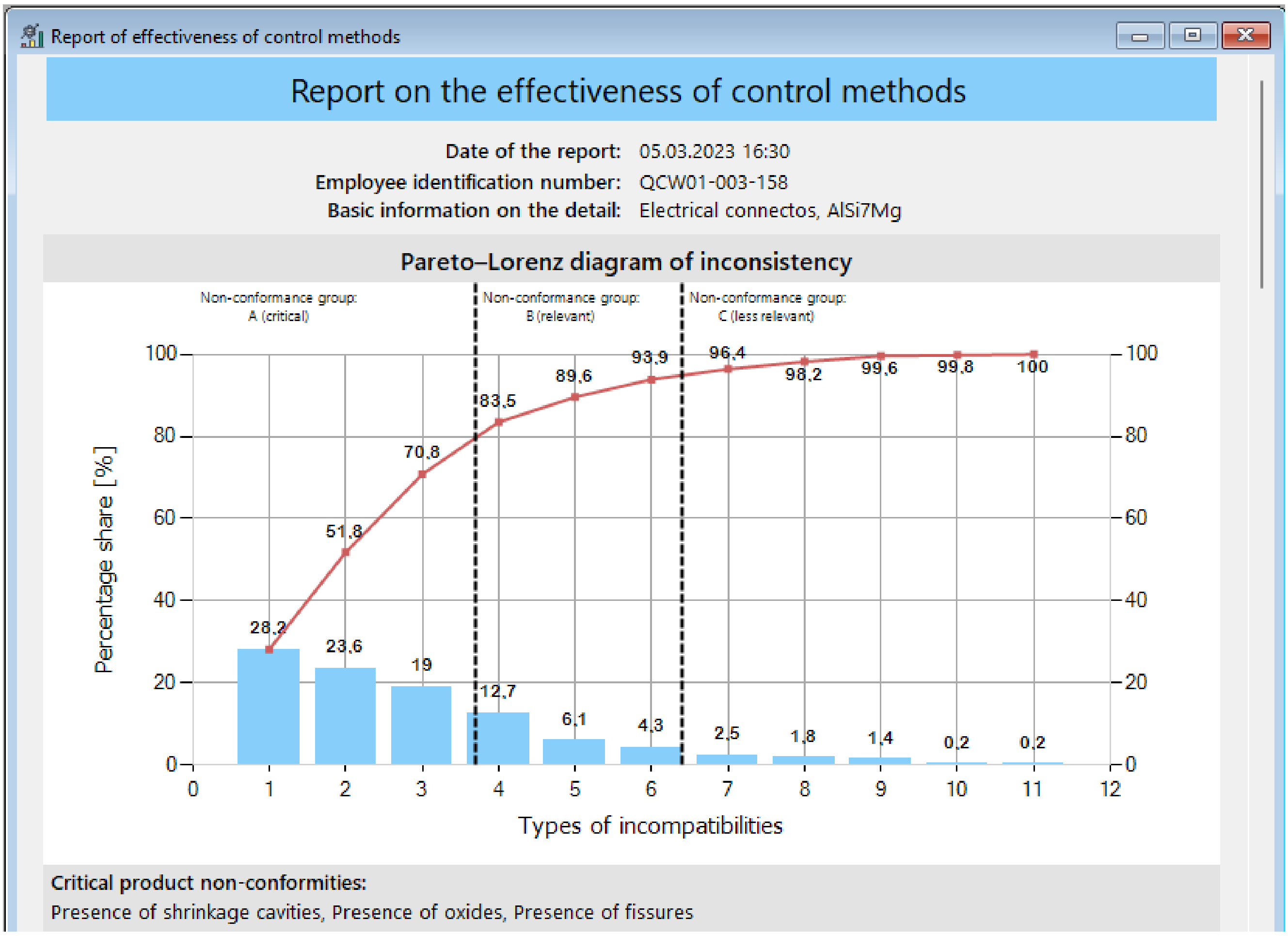

Figure 6. Part one of the report on the effectiveness of control methods: Pareto–Lorenz chart.

The markings on the horizontal axis of the graph indicate control methods identical to those in Figure 5.

Based on the electrical connector results of the quality control and the Pareto–Lorenz diagram developed in the report (Figure 6), the presence of shrinkage cavities, the presence of oxides, and the presence of fissures were considered critical incompatibilities. According to the assumptions of the Pareto–Lorenz diagram and the principle of interpreting its results, critical nonconformities account for about 30% of the causes bringing about 70% of the losses. Two of the three critical nonconformities are identified most often with the use of radiography (presence of shrinkage cavities and presence of fissures), whereas the nonconformity presence of oxides is most often identified with the use of ultrasound.

The next part of the report concerns the identification of the level of efficiency of detection methods. For this purpose, formula (1) from Table 2 is used, and the results are presented in a matrix diagram divided into quadrants. The desired situation is to reach quadrant II of the matrix diagram, which indicates that the control occurs less frequently, but detects more nonconformities. The result of the effectiveness assessment is shown in Figure 7.

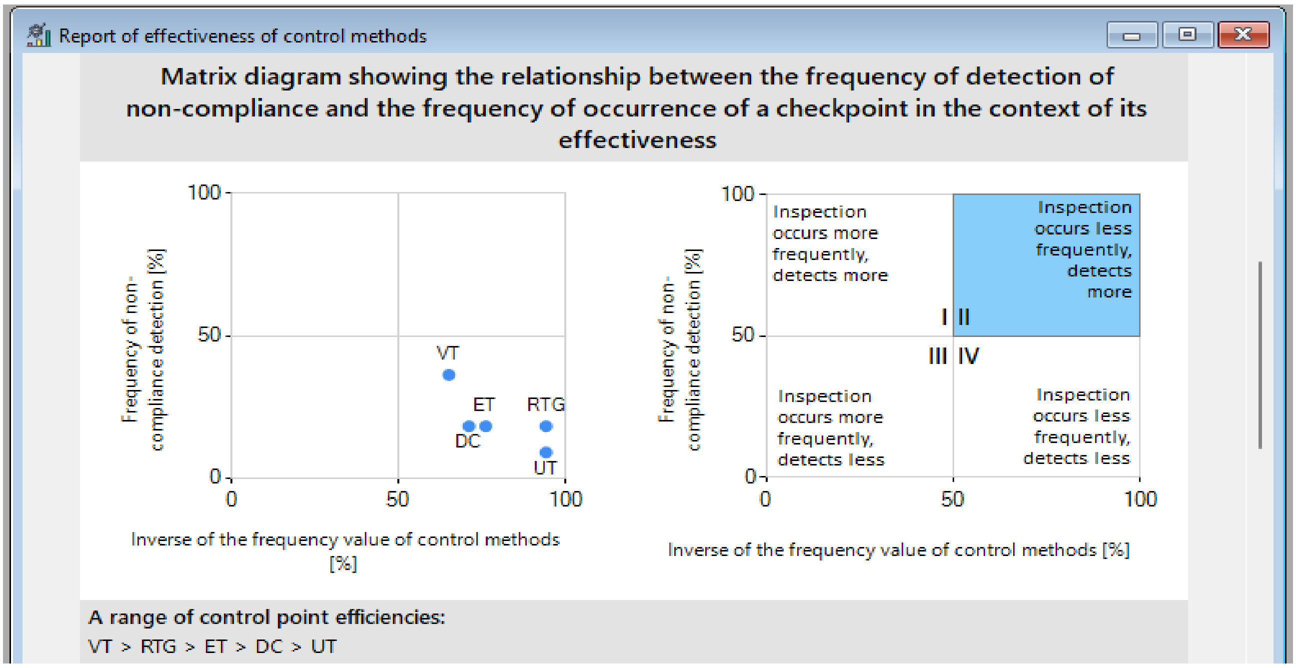

Figure 7. Part two of the report on the effectiveness of control methods—analysis of the level of effectiveness of detection methods.

In Figure 7, the matrix diagram on the left shows the obtained values of the effectiveness level: that is, the relationship between the frequency of identification of nonconformities and the frequency of the detection method within the entire production process. The diagram on the right is an overview diagram to facilitate the interpretation of the results obtained.

Based on the values obtained, a ranking of the efficiency of detection methods was created, according to the principle that the more, the better. The efficiency values of the individual methods are as follows:

$$S_{VT} = 36.4\% \cdot (1 - 35.0\%) = 23.7\% \tag{6}$$

$$S_{RTG} = 18.2\% \cdot (1 - 6.0\%) = 17.1\% \tag{7}$$

$$S_{ET} = 18.2\% \cdot (1 - 24.0\%) = 13.8\% \tag{8}$$

$$S_{DC} = 18.2\% \cdot (1 - 29.0\%) = 12.9\% \tag{9}$$

$$S_{UT} = 9.1\% \cdot (1 - 6.0\%) = 8.6\% \tag{10}$$

The high level of effectiveness of visual inspection (23.7%) is significantly influenced by the significant frequency of the method within the production process and the high level of nonconformity detection. The lowest level of effectiveness is characterised by the ultrasonic method (8.6%). This indication is due to the low frequency and relatively low level of nonconformity detection. However, it should be noted that the nonconformities identified by the UT method are critical nonconformities.

In the next step of analysing the efficiency of the detection methods, the cost-effectiveness of the checkpoints was examined, as shown in Figure 8.

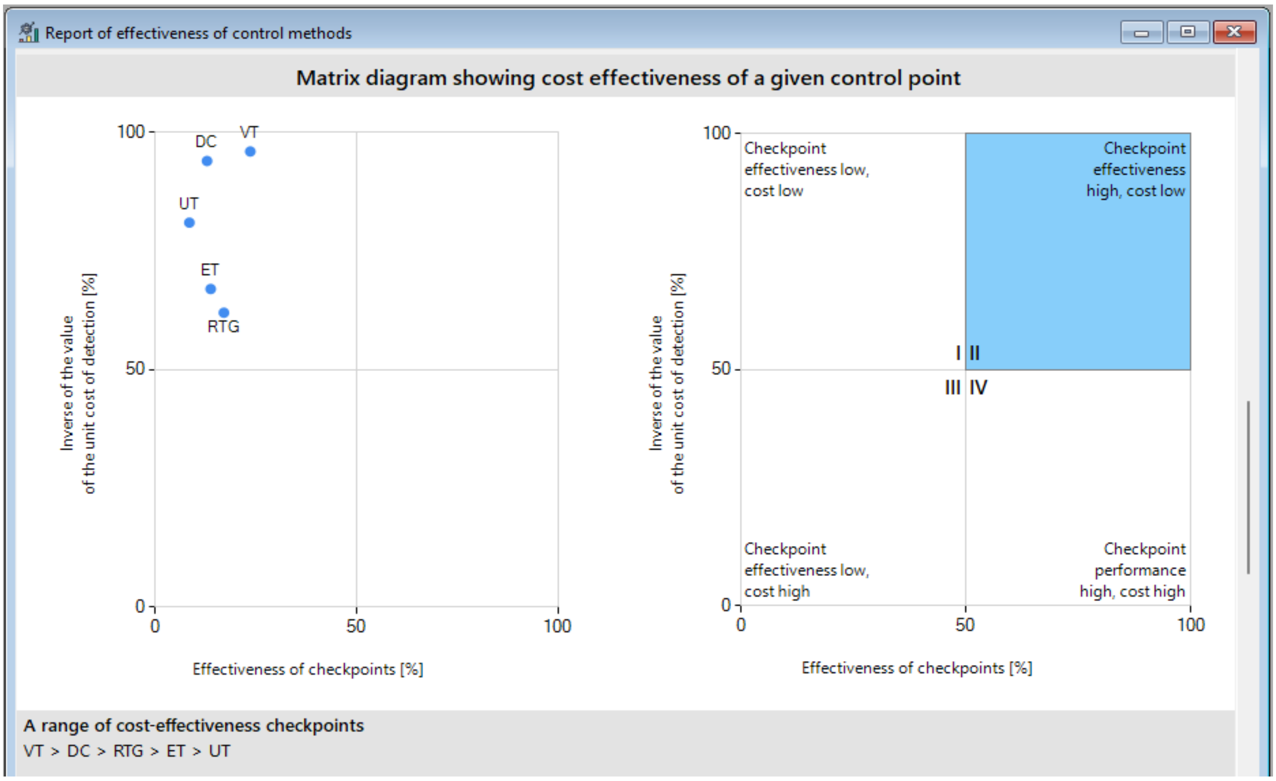

Figure 8. Part three of the report on the effectiveness of control methods—analysis of the level of cost-effectiveness of detection methods.

The parameters achieved qualify the detection methods to the first quadrant of the matrix diagram, indicating that, in general, inspections are implemented with relatively low efficiency and relatively low cost of testing (Figure 8). The most expensive tests within the studied process are X-ray tests. The cost-effectiveness values of the various methods are as follows:

$$EK_{VT} = 23.5\% \cdot (1 - 4.0\%) = 22.6\% \quad (11)$$

$$EK_{DC} = 12.8\% \cdot (1 - 6.0\%) = 12.0\% \quad (12)$$

$$EK_{RTG} = 17.1\% \cdot (1 - 38.0\%) = 10.6\% \quad (13)$$

$$EK_{ET} = 13.9\% \cdot (1 - 33.0\%) = 9.3\% \quad (14)$$

$$EK_{UT} = 8.6\% \cdot (1 - 19.0\%) = 7.0\% \quad (15)$$

The high level of the cost-effectiveness of VT inspection is influenced by its significant level of efficiency and (despite the high prevalence of this method) the low cost of implementing the tests. The most costly tests within the studied process are X-ray tests, making their cost-effectiveness only 10.6%.

The next part of the analysis was concerned with determining the level of the time efficiency of detection methods. The part of the report that indicates the result of the study is shown in Figure 9.

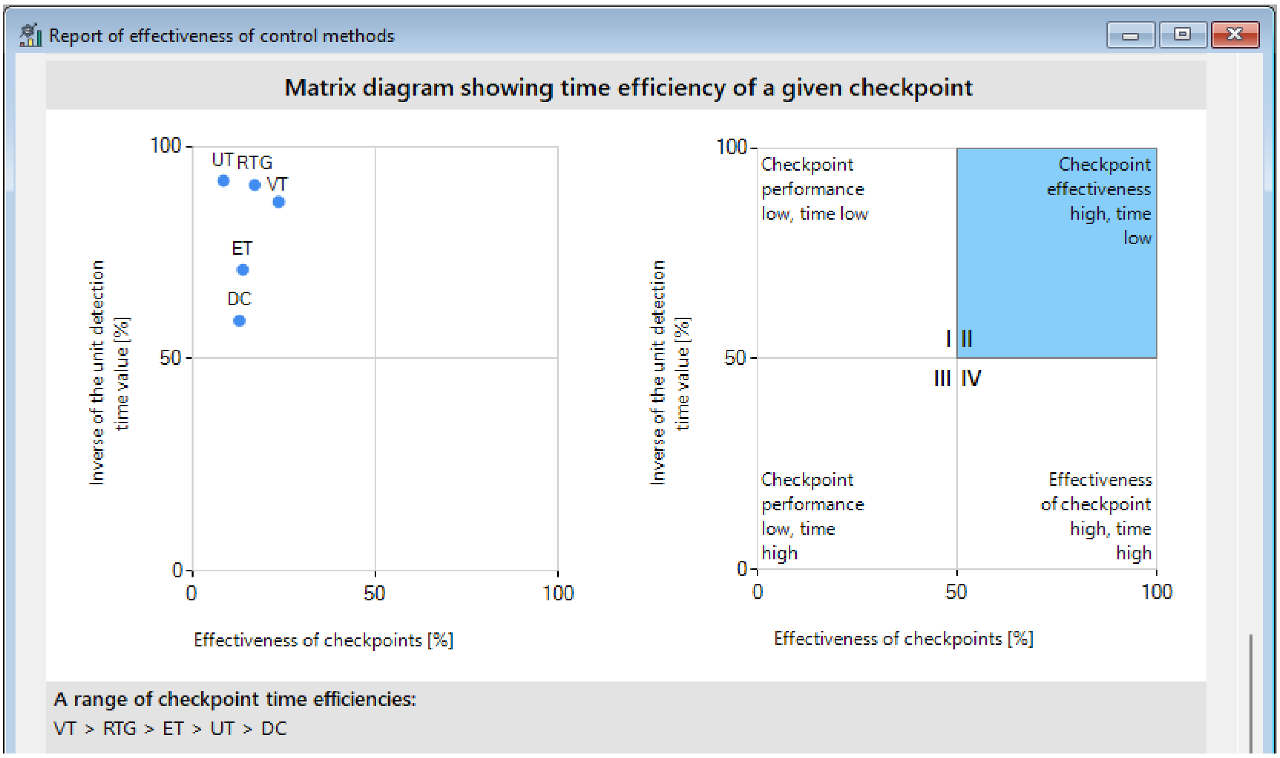

Figure 9. Part four of the control methods efficiency report—analysis of the level of time efficiency of detection methods.

As in terms of cost efficiency, so in terms of time efficiency, the detection methods were located in the first quadrant of the matrix diagram (checkpoint efficiency relatively low and detection execution time relatively low) (Figure 9). The shortest detection time is characterised in the case analysed by the ultrasonic method. Individual values of the time efficiency parameter of the detection methods have the following values:

$$EC_{VT} = 23.5\% \cdot (1 - 13.0\%) = 20.4\% \tag{16}$$

$$EC_{RTG} = 17.1\% \cdot (1 - 9.0\%) = 15.6\% \tag{17}$$

$$EC_{ET} = 13.9\% \cdot (1 - 29.0\%) = 9.9\% \tag{18}$$

$$EC_{UT} = 8.6\% \cdot (1 - 8.0\%) = 7.9\% \tag{19}$$

$$EC_{DC} = 12.8\% \cdot (1 - 41.0\%) = 7.6\% \tag{20}$$

In terms of cost-effectiveness of detection methods, the VT method received the highest indication, which was mainly influenced by the high efficiency parameter and the relatively short detection time. The longest detection time is associated with the control of electrical joint dimensions because of the complex geometry of the product and the lack of automation of the control.

The energy intensity of the detection methods was also analysed by relating it to the efficiency parameter of the methods. The result is indicated in Figure 10.

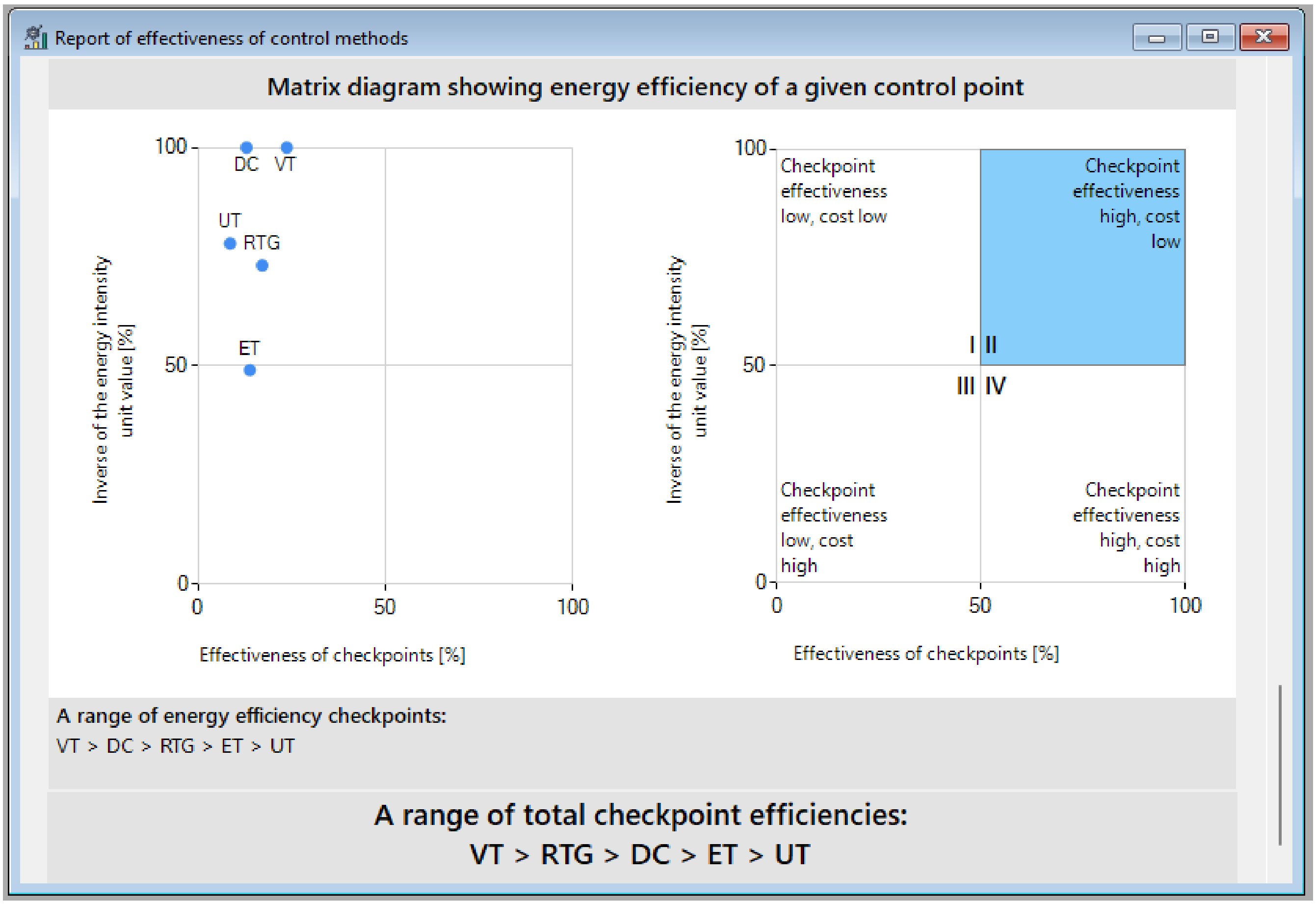

Figure 10. Part five of the control methods efficiency report—analysis of the level of energy efficiency of detection methods and ranking of the total efficiency of detection methods.

The energy efficiency ranking of the control methods shown in Figure 10 was based on the following parameters:

$$EE_{VT} = 23.5\% \cdot (1 - 0\%) = 23.5\% \quad (21)$$

$$EE_{DC} = 12.8\% \cdot (1 - 0\%) = 12.8\% \quad (22)$$

$$EE_{RTG} = 17.1\% \cdot (1 - 27.0\%) = 12.5\% \quad (23)$$

$$EE_{ET} = 13.9\% \cdot (1 - 51.0\%) = 6.8\% \quad (24)$$

$$EE_{UT} = 8.6\% \cdot (1 - 22.0\%) = 6.7\% \quad (25)$$

Both the VT and DC tests are not energy-intensive tests; hence, the effectiveness–energy intensity relationship indicates the leading ranking of these methods. Analysing the energy-intensive detection methods, that is, X-ray, ET, and UT, it can be observed that the most favourable indication in the context of the studied relationship is shown by radiographic examination (12.5%). Despite the significant level of energy intensity per unit examination by this method, the influence of the other key parameter variables (frequency of detection method and frequency of identification of nonconformities) indicates that this method has about a 5% advantage over ET and UT methods. The parameters of the ultrasonic and eddy current methods in terms of energy efficiency are virtually identical in the inspection process studied.

Part five of the report (Figure 10) also includes a ranking of the total efficiency of the detection methods. This ranking was made according to the following indications:

$$E_{VT} = 23.5\% \cdot 22.6\% \cdot 20.5\% \cdot 23.5\% = 0.256\% \tag{26}$$

$$E_{RTG} = 17.1\% \cdot 10.6\% \cdot 15.6\% \cdot 12.5\% = 0.035\% \tag{27}$$

$$E_{DC} = 12.8\% \cdot 12.1\% \cdot 7.6\% \cdot 12.8\% = 0.015\% \tag{28}$$

$$E_{ET} = 13.9\% \cdot 9.3\% \cdot 9.9\% \cdot 6.8\% = 0.009\% \tag{29}$$

$$E_{UT} = 8.6\% \cdot 6.9\% \cdot 7.9\% \cdot 6.7\% = 0.003\% \tag{30}$$

The high value of the total efficiency index of the VT survey is largely influenced by the low cost of implementing detection and the lack of electricity consumption during the survey. For similar reasons, dimensional inspection ranked third in total efficiency. Other detection methods (X-ray, ET, and UT) are characterised by higher parameters that describe detection, mainly the cost and level of energy consumption. Due to the significant discrepancies that characterise the methods when interpreting them, it is necessary to create two separate rankings, thus distinguishing between methods implemented automatically or semi-automatically and methods implemented by personnel. The form of the rankings is as follows:

$$\text{Methods implemented by staff:} \quad VT > DC \tag{31}$$

$$\text{Methods implemented automatically or semi-automatically:} \quad RTG > ET > UT \tag{32}$$

Visual inspection in each of the presented rankings shows that this control significantly outperforms the effectiveness of dimensional inspection. With the use of this type of inspection, 4 of the 11 listed product nonconformities (edge splitting, fogging, underfill, and scratches) are most often identified. This contributes to the high level of effectiveness of the method.

Analysing the result of the ranking (32), it is important to note the X-ray examination, whose value of the total efficiency index significantly exceeds the parameters of the other methods. This fact underscores the importance of using the X-ray method in the context of ensuring a stable level of quality and detecting critical nonconformities. Despite the highest energy consumption per unit of X-ray detection, the method has the highest level of total efficiency. Quality control using eddy current testing and ultrasound testing achieved the smallest differences in the level of total efficiency. Although the eddy current method outperforms the ultrasound method in each of the rankings, within the analysed process, it is not recommended to abandon the ultrasound method in the near future. This method shows effectiveness in identifying the critical nonconformity (presence of oxides) facing the company.

The application presented in the paper, based on the proposed model for analysing the level of efficiency of checkpoints in the context of energy intensity, enables effective quality and energy management in manufacturing enterprises. The developed model goes beyond passive quality control. It not only refers to the identification of nonconformities and the monitoring of the quality level, but it supports decision-making and management processes regarding the effective placement of control methods. The model takes into account a number of variables that have a significant impact on the effectiveness of ensuring an adequate level of quality of the products offered while ensuring rational energy management. These variables include the frequency of a specific detection method, the frequency of detection of critical and significant nonconformities, and the time, cost, and energy intensity of a single detection. The use of the proposed model makes it possible to study the correlations that occur between the indicated variables, which, in relation to the priorities of companies, supports the optimisation of checkpoints.

The versatility of the software allows the user to introduce an additional detection method if one has not been included and to expand the library of nonconformities if necessary.

4. Results and Discussion

A survey of the literature relating to energy intensity and the reduction of the cost of energy consumption of individual companies in the manufacturing sector indicates that attempts are being made to create methods and optimisations. Examples include the method developed based on production scheduling in small and medium enterprises [90] or methods based on indicator analysis [91]. However, the most common studies in the area of energy intensity analysis in individual companies are concerned with the implementation of energy audits to identify all energy streams [92]. With the help of an audit, it is possible to quantify energy consumption and to try to balance energy input with energy consumed [93]. Audit can refer to energy management as a whole company (balance audit) or to selected elements related, among others, to heat sources, building infrastructure, electricity and heat generation systems, renewable energy sources, lighting systems, air conditioning and mechanical ventilation systems, as well as waste heat [94]. However, it is difficult to find studies in which energy audit refers to the analysis of the energy intensity of quality control as a separate field of analysis. Furthermore, the implementation of an energy audit does not allow the study of the correlation between product quality and the intensity of detection methods [95].

It was noted that the literature lacks methods for managing the energy efficiency of automated detection methods. There is a research gap within management using standardised indicators directly related to the analysis of energy consumption in the area of quality control. Analytical methods and effective management have not caught up with the progress in widely used automation and electronics. Furthermore, it was noted that there is a lack of studies on comparisons of detection methods in terms of their level of energy efficiency to determine their validity and create a ranking of methods. Therefore, the aim of the research was to develop the author's software based on a model that allows a realisation of the analysis of the relationship between product quality, energy intensity of the detection method, and the level of efficiency of the total detection methods of cast aluminium alloy products in the context of their energy intensity. The classification is based on the complete analysis of data from the unit quality control. Determining the rank of detection methods used within the production process makes it possible to perform optimisation by: controlling the amount of detection performed by a given method, controlling the placement of inspection points, and determining the frequency of detection activities (random inspection or 100% inspection). These actions will allow us to obtain the desired balance between the relationship of product quality and the energy intensity of detection, or its cost or time.

The developed model of proceeding in comparison with the methods of diagnosing energy intensity used in production enterprises allows conducting multifaceted analyses. The methods described in the literature boil down to only overseeing energy flow paths in a manufacturing company and identifying outstanding energy-intensive areas or predicting electricity production and consumption (methods characterised in Table 1). These approaches do not fully manage energy consumption effectively, as they provide too little information needed for optimisation projects. The models in Table 1 analyse too few variables to adequately reflect reality. In contrast, methods based on scheduling [91] or indicator analyses [92,93] provide a broader spectrum of information but capture the enterprise as a whole—there is no clear separation of qualitative process analyses. In the literature, it is hard to find a method that refers to optimisation activities regarding the energy intensity of quality assurance processes. The identified research gaps are filled with the developed method of checkpoint efficiency analysis. In addition, the developed model does not only apply to energy analyses but also to energy quality analyses of the selected quality control process. The presented model allows one to analyse not only the intensity of energy in the area of quality management, but also to take into account the other two key aspects from the point of view of the operation of manufacturing enterprises: the cost of detection implementation and the time of detection implementation. The developed model allows us to take optimisation measures in accordance with the assumptions of sustainable development. An advantage is the possibility of integrating the proprietary CmEfficiencyNew software with automated detection equipment to perform ongoing monitoring of energy intensity and quality levels. This procedure will save time in the execution of the analysis and allow us to react quickly in situations of loss of process stability.

A test of the proprietary CmEfficiencyNew software was carried out to determine its suitability in the field of energy quality management of the production process of an electrical connector. The verification of the software identified the most dangerous nonconformities, critical ones, which turned out to be the presence of shrinkage cavities, the presence of oxides, and the presence of fissures identified mainly by X-ray and ultrasonic testing. When developing a ranking of the total efficiency of the detection methods analysed, the following variables were taken into account: efficiency, cost, time, and energy intensity of unit quality control. A comprehensive account of the partial rankings and the final ranking on the effectiveness of the total detection method is shown in Table 3.

Table 3. Rankings of detection methods in relation to analysed variables.

Index	Ranking of Detection Methods	
Effectiveness of detection methods	VT > RTG > ET > DC > UT	(33)
Cost-effectiveness of detection methods	VT > DC > RTG > ET > UT	(34)
Time efficiency of detection methods	VT > RTG > ET > UT > DC	(35)
Energy efficiency of detection methods	VT > DC > RTG > ET > UT	(36)
Total efficiency of checkpoints	VT > RTG > DC > ET > UT	(37)

Based on the data in Table 3, it can be seen that among the automated methods, the X-ray method (despite the highest level of energy intensity) proved to be crucial within the production process. This result is largely determined by the high level of efficiency (identification of two of three types of critical nonconformities) and automation of the test. Among the inspection methods carried out by personnel, the level of total efficiency of visual inspection exceeds that of dimensional conformity inspection. This is influenced by the low parameters related to the time and cost of implementation and the ability to identify different types of casting nonconformities.

In view of the observed facts and opportunities presented by the CmEfficiencyNew programme, discussions should be initiated on conducting energy efficiency analysis of control methods independently of conventional cost–benefit analyses.

5. Conclusions

The growing demand for the respect and use of natural energy sources has a significant impact on the rising prices of these raw materials. This, in turn, directly affects the cost of producing electricity. Therefore, the objective is to achieve the lowest energy intensity of manufacturing processes. In the case of the energy intensity of product manufacturing, an important issue is also the energy intensity of quality control processes, which are increasingly automated these days. For this reason, the purpose of the study was to present software based on a model that enables the analysis of the level of efficiency of detection methods for cast aluminium alloy products in the context of their energy intensity. The developed model supports the effective management of the quality control process, with emphasis on optimisation of the relationship of product quality with energy intensity of the process.

The developed software is based on a model that combines control methods and their analyses. The analyses make it possible to examine the level of efficiency of automated and non-automated control methods, which is examined in relation to their effectiveness, cost efficiency, time efficiency, and efficiency in terms of energy intensity of a unit test. The analytical software presented takes into account the identification of correlations that occur between the efficiency of the detection method and the time, cost, and intensity of the test. This activity supports the determination of the detection methods' total efficiency of the level and the determination of their rank and level of importance. The presented approach makes it possible to identify checkpoints that identify critical nonconformities of the product while taking into account the variables analysed.

The verification of the model proved that reasonable management of checkpoints has a positive effect on ensuring the continuity of manufacturing processes, early identification of nonconformities in products, and reducing the cost of the quality control process and the manufacturing process. The compiled ranking of the efficiency of detection methods applied to the electrical connectors indicates the benefits in terms of the automation of detection methods. This fact is confirmed by the automated X-ray inspection value of the total efficiency index (0.035%), which significantly exceeds the values obtained for eddy current testing (0.009%) and ultrasonic testing (0.003%). The parameters obtained from the total efficiency index in relation to the methods carried out by personnel take higher values (visual inspection, (0.256%) and dimensional inspection (0.015%)). This is mainly influenced by the lack of energy intensity and the low cost of detection. This conclusion alludes to the totality of Industry 4.0 assumptions.

Thanks to the verification of CmEfficiencyNew software to analyse the effectiveness of detection methods, it was observed that:

- the software allows one to configure detection methods integrally, which contributes to reducing the level of diagnostic uncertainty;
- the software allows one to identify critical inconsistencies of the analysed casting that affect significantly the formation of quality problems;
- the software allows one to make quality analysis and appropriate corrective actions (going beyond passive control);
- the software allows one to organise and collect data on the specifics of detection methods and identified nonconformities;
- the software makes it possible to determine the level of effectiveness, time efficiency, cost, and energy intensity of detection units;
- the software makes it possible to create a ranking of the total efficiency of checkpoints;
- the software allows comparison of selected detection periods;
- the use of software will facilitate the improvement of the quality control process in terms of maintaining optimum relationships between product quality and energy intensity of detection methods.

The identified opportunities brought about by the implementation of CmEfficiencyNew software in the area of quality management and energy management of enterprises contribute to:

- rationalisation of electricity consumption levels;
- optimisation of the distribution of checkpoints within the entire production process (reducing the cost and time of the quality control process);
- elimination of waste (product inconsistencies, overproduction, and waiting);
- reduction of production costs;
- conscious response in situations of loss of quality stability of products: acceleration of the decision-making process to carry out improvement activities.

Manufacturing companies can implement inspection activities and manage inspection points in different ways, but the proposed CmEfficiencyNew software to analyse the effectiveness of detection methods is a useful tool for conducting research on the relationship between product quality and process energy intensity. Due to the clarity of the interface, the extensive libraries of detection methods and potential casting nonconformities, and the universal nature, the proposed software can be successfully used in various organisations. Further key development steps of CmEfficiencyNew software will be related to the expansion of the application with modules that allow the implementation of additional quality energy analyses. However, further steps concerning the company where the software was tested will concern the implications for the company's other products in order to optimise the quality control process.

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