SSRG International Journal of Economics and Management Studies
ISSN: 2393–9125 / https://doi.org/10.14445/23939125/IJEMS-V12I12P102

Volume 12 Issue 12, 8-14, December 2025

Original Article

Evaluation of Exergy Costs within the Scope of Quality Costs

Özlem Koçakoğlu[1], Mehmet Ali Koçakoğlu[2]

[1]*Şanliurfa Social Sciences Vocational High School Accounting and Tax Practices, Harran University, Türkiye.*
[21]*Şanliurfa Social Sciences Vocational High School Foreign Trade, Harran University, Türkiye.*

[1]*Corresponding Author : alikocakoglu@harran.edu.tr*

Received: 22 October 2025 Revised: 24 November 2025 Accepted: 15 December 2025 Published: 31 December 2025

Abstract *- The concept of quality has been defined from different perspectives in the literature. One of the most common and accepted definitions is Juran's approach, which refers to quality as "the suitability of a product or service for customer use". Quality costs, on the other hand, include the costs arising from the existing poor quality and the costs incurred to prevent poor quality and reach the desired quality level. In the literature, quality costs are generally classified as prevention costs, evaluation costs, and error costs. The concept of Exergy, on the other hand, provides information about the general efficiency of the system by measuring the thermodynamic performance of production systems and reveals how much of the energy entering the system is converted into practical work. It quantitatively determines the losses in energy and resource quality by revealing the points where irreversibility in the production system is concentrated. Exergoeconomic analysis involves calculating the monetary equivalent of these losses. This study aims to discuss whether exergy-based inefficiencies can be handled from the perspective of quality costs. Thus, prevention, evaluation, and error costs; Exergy is associated with destruction and loss, creating a holistic decision support structure for continuous improvement and cost reduction.*

Keywords *- Excesses, Types of Maliciousness, Exoreconomics, cost account, Exergy.*

1. Introduction

Quality is a concept that cannot be gathered under a single definition in the literature and is handled in various dimensions by different disciplines. One of the most accepted approaches in the field of quality management is the view put forward by Juran, which defines quality as the degree to which a product or service meets user requirements. Quality costs, on the other hand, include the costs arising from the existing poor quality and the costs incurred to prevent poor quality and reach the desired quality level. In the literature, quality costs are generally classified under three main headings: prevention, evaluation, and error costs.

Exergy is a concept that expresses the maximum practical work that the energy entering a production system can produce until it reaches equilibrium with the environment, and measures the quality of energy. Exergy analysis allows us to determine how much of the energy entering the system contributes to the production process, and how much becomes unusable due to physical processes within the system. In this way, inefficiencies that arise in production systems are evaluated not only in terms of quantity but also in terms of quality; It can be quantitatively revealed at which stages the losses in energy and resource use are concentrated. In this respect, exergy analysis offers an important analysis tool in evaluating the performance of systems and determining improvement potentials.

Exergoeconomics, on the other hand, aims to calculate the monetary equivalent of these inefficiencies that arise in the production process by combining exergy analysis with economic evaluation. Within the scope of exergoeconomic analysis, losses in energy and resource use are correlated with costs, so that it can be determined which components of the system increase costs. This approach provides a holistic and rational decision support framework for system design, improvement, and investment decisions, considering not only the level of energy consumption but also the extent to which energy is used effectively.

However, how these inefficiencies revealed by exergy analysis in production systems can be positioned within the framework of quality costs has not been adequately discussed in the literature. However, while it is possible to convert energy and resources into products at a higher rate, considering the losses arising from systemic problems and thermodynamic limits within the scope of quality costs can bring a different perspective to production processes. This study aims to discuss whether exergy-based inefficiencies can be evaluated from the perspective of quality costs and to provide a holistic decision support framework for continuous improvement and cost reduction by associating prevention, evaluation, and error costs with exergy destruction and exergy loss.

2. Quality Costs

Quality is a multifaceted concept. Quality, according to Taguchi, It is the least harm caused by the product to society after shipment. According to Juran, quality is suitability for use. It is a production that provides customer satisfaction and does not have defects. According to Crosby, quality is compliance with needs. According to Feigenbaum, quality is the combination of marketing, engineering, production, and maintenance characteristics at the point where the product or service meets the expectations of the customer (Kurşunel & Güzel, 2015:286). Juran characterized the benefits of the phenomena of "no defects" and "customer satisfaction", which form the basis of the definition of quality, as follows (Juran, 1999, 2.2)

Table 1. The Meaning of Quality

Ensuring Customer Satisfaction (High quality in this regard makes the following features possible for the business)	**Absence of Fault** (High quality in this regard makes the following features possible for the business)
It increases customer satisfaction. It makes products salable. It introduces competition. It increases its market share. Generates sales revenue It provides secure premium prices. The most significant impact is on sales. Usually, better quality is more expensive.	Reduces error rates Reduces rework and waste Reduces field failures. Reduces warranty charges. It reduces customer dissatisfaction. It reduces inspection and. testing. It reduces the time to bring new products to market. It increases efficiency and capacity. Improves delivery performance. The most significant impact is on costs. Generally, better quality is less costly.

The meaning of quality and the fundamentals of competing in today's conditions coincide exactly. The above features have been the key to competition for many businesses since 1990, when they were defined by Juran, and are still being followed. Businesses must carry out activities that will increase the quality level and work to prevent errors that reduce product and service quality. Since carrying out these studies will bring with it the costs to be incurred, it is extremely important to know and closely monitor these costs. (Bekçi and Toraman, 2011: 40). In achieving quality targets, it is only possible to see and manage the quality-cost relationship by calculating these costs. The quality cost system plays a critical role in the business by identifying, measuring, and controlling the causes of poor quality and identifying areas that require improvement. The measurement of quality costs was first made by Armand Feigenbaum in 1956. It has divided quality costs into 3 categories. These are "prevention costs", "evaluation costs", and "error costs". The British Standards Institution and the American Society for Quality Control have adopted this classification and included it in their standards, thus ensuring its widespread use (Bris, Cermakova, & Molnar, 2022: 450). Error costs are further broken down by Juran into external and internal failure costs (Rasamanie & Kanapathy, 2011:244).

2.1. Prevention Costs

Prevention costs are the costs incurred to reduce evaluation costs and achieve minimum error. It is defined as expenditures made in efforts to prevent low quality (Sezal, 2017: 1112). Prevention costs are the costs incurred by the activities related to the design, creation, and placement of the quality system within the organization (Yıldıztekin, 2005:406). It consists of the sum of the costs related to the planned process to ensure that errors do not occur. Prevention costs can be counted as follows (Tanış& Kefe, 2017:183).

- Quality engineering.
- Quality planning.
- Design and development of quality equipment.
- Quality training.
- Quality improvement projects.
- Collection and analysis of quality data.
- Statistical process control.
- Other control processes to prevent errors.
- Cost accounting for production deviations.
- Supplier guarantee and quality inspection.

In a literature review study conducted in 2024, Patel and Desai classified the costs of prevention as follows. This classification includes more dynamic features than the classical prevention cost classification (Desai & Patel, 2024:30).

- Cost/module design costs related to research, design, testing, and development of a new product according to customer requirements
- Costs associated with developing the procedure to ensure compliance with standards, enhance the improvement effort, and ensure compliance with legal regulations and standards set by the industry
- Outsourced consultancy and expertise costs depend on the scope and complexity of the problem.
- Costs incurred to access potential suppliers or to evaluate existing suppliers.
- Costs associated with regular calibration of tools and panels to maintain adequate functioning of manufacturing processes, to minimize errors, and maximize quality.

- Quality improvement team purchases and programs. Costs associated with building a quality improvement team that focuses on raw material purchase to shipping the final product.
- Quality education and training. Costs related to supporting lifelong learning that will improve the working environment, providing quality education on processes.
- Costs associated with determining customer demands and satisfaction.
- Costs incurred in hiring knowledgeable and efficient human resources.
- The cost associated with process improvement, such as identifying bottlenecks, improving employee morale, etc.

2.2. Evaluation Costs

These are the costs arising from the measurement, execution and inspection activities carried out to determine whether the produced product complies with the specifications determined during the design phase throughout the production line (Koç & Demirhan, 2007:89). In other words, evaluation costs include the expenses incurred for the control, testing, inspection, review and valuation studies of the inputs before the product to ensure the degree of conformity to the quality made during the design phase of the product (Çabuk, 2005:3). The rationale behind this hypothesis is rooted in the premise that early detection of quality variations through robust evaluation metrics can lead to a reduction in defective cases, thereby positively impacting a company's operational efficiency and customer satisfaction. This leads to reduced expenses related to rework, scrapped material, warranty claims, customer complaints, and legal issues; all of which are classified as failure costs within the Quality Cost framework (Owusu, Afriyie, Ababio, Owusu, 2024:1435). The following costs are the costs incurred to determine the degree of compliance with quality requirements (Gryna, 1999:8.7).

- Inspection and testing: Determining the quality of the purchased product, either through inspection at the time of delivery, inspection at the source, or through surveillance.
- In-process inspection and testing: In-process assessment of compliance with requirements.
- Final inspection and testing: Assessing compliance with requirements for product acceptance.
- Document review: Examination of the documents to be sent to the customer.
- Balancing: Reviewing various accounting accounts to ensure internal consistency.
- Product quality inspections: Conducting quality inspections on in-process or finished products.
- Maintaining the accuracy of test instruments: Keeping measuring instruments and equipment calibrated.
- Inspection, testing materials and services: Materials and services in inspection and testing, where important (e.g., X-rays)
- Assessing stocks: Testing products in the field, warehouse, or in stock to assess spoilage.

2.3. Failure Costs

These are the costs incurred when products or services do not comply with requirements or customer expectations. Failure costs are divided into two categories: internal and external costs.

2.3.1. Internal Failure Costs

These costs are incurred when the business results fail to reach the designed quality standards and are detected before delivery to the customer (Kumar & Hubaishi, 2021: 561). It can be classified as follows (Patel & Desai, 2024, p. 31).

- Scrap: The cost of raw materials and products lost during the production process.
- Material Reprocessing/ Recycling: The costs associated with scrapping products and services require additional processes to achieve quality standards that may not be achieved the first time.
- Reprocessing Personnel: Costs associated with reprocessing, which is carried out by employing manpower for the reuse of waste material.
- Re-Inspection and Retesting: Costs associated with re-inspecting and retesting the recycled material.
- Internal failure analysis: Costs associated with product failures detected through an internal inspection process prior to the shipment of products.
- Negative evaluation by management: Negative change in the evaluation of the product compared to the competitor's product
- Scarcity: The costs incurred to overcome a scarcity situation that occurs when demand outweighs supply.
- Delay: Costs incurred due to an unknown or ignored reason, unnecessary time increase, or postponement.

2.3.2. External Failure Costs

These costs are incurred by realizing the deficiencies of the product after it reaches the customer. In addition, sales revenues, in other words, will pose a threat to potential customers. These costs can be significantly reduced by eliminating the deficiencies in the production and transportation process (Kurşunel & Güzel, 2015:288).

External failure costs can be listed as follows (Demircioğlu and Küçüksavaş, 2009:45):

- Complaint Investigations; are the costs of investigating, resolving, and responding to customer complaints.
- Unaccepted and Returned Goods; These are the costs incurred because of the evaluation, repair, or renewal of products that do not meet the quality requirements and expectations of the customer and do not satisfy the customer.
- Correction Costs: It is only the cost of corrections made due to quality problems.

- Lost Sales: These are the costs of loss of profit covered because of a decrease in sales due to the poor-quality product not satisfying the customer.
- Customer Reputation: These are fictitious costs incurred because of the customer not staying with the distributed product.
- Obligations Fulfilled During the Warranty Process; It is the cost of some services provided to the customer in accordance with the contract and laws after the product is offered.
- Commitment Costs: These are the costs paid by the company due to commitment demands and include the insurance costs of the product or service.
- Penalties: It is the cost of the penalties incurred because of the failure to perform the product or service, or the non-performance of the product or service in accordance with the laws or agreements made with the customers

3. Exergy Costs

Exergy is the ability of energy to do work. Exergy analysis helps to determine the amount and nature of thermal losses of systems. (Özdemir & Yatarkalkmaz, 2015: 243).

Without going against any law of thermodynamics, it represents the upper limit on the amount of work that a mechanism can give (Yılmaz, 2018:2).

The monetary expression of energy losses found by using thermodynamic laws falls within the scope of exergoeconomic analysis. This concept arose from the need to evaluate both the thermodynamic and economic performance of energy-powered systems together. This approach allows for a monetary assessment of the costs caused by irreversibility (exergy losses—energy not being converted into work, irreversibly disappearing) and also for comparisons between these costs and investment and operating costs for each component of a plant (Tsatsaronis & Winhold, 1985:69). While the laws of thermodynamics are insufficient to examine only quantity changes with energy analysis, exergy analysis is based on the capacity of energy to do work. It makes the irreversibility in the system visible. Therefore, exergy cost is accepted as a method that calculates the real economic load of a product not only on energy consumption, but also on exergy losses and destruction throughout the process. Economic analysis tracks the flow of economic value of material and energy flows into and out of the total system or subsystems. In the combination of exergetic and economic analysis, both exergy flows and economic value streams are analyzed, and their interdependence is determined (Tsatsaronis & Winhold, 1985:70). Exergy provides a business with the benefit of measuring the following issues and expressing them in monetary terms (Tsatsaronıs, 1993:231).

- A measurement to be able to understand the magnitude of "energy waste" in relation to the "energy" supplied or converted in the plant and in the component analyzed.
- A measurement of the quality (or usefulness) of energy from a thermodynamic point of view.
- A variable that defines rational efficiency for energy systems.

The exergoeconomic analysis follows a structured methodology that begins with a detailed exergy analysis of the energy conversion system. The first step is conducting detailed mass, energy, and exergy balances (thermodynamic analysis) for the total plant. The mass, energy, and exergy flow rates of all process flows are calculated using detailed equilibrium formulations. The exergetic efficiency of each plant component is defined and calculated. Thermodynamic analysis allows the location and magnitude of exergy losses to be investigated (Tsatsaronis & Winhold, 1985:71). To perform technical analysis, system components must be examined separately. For example, in a steam power cycle, the inlet and outlet exergy for each of the boilers, turbines, condensers, pumps, and heat exchangers are determined, the exergy destruction is calculated, and the contribution of this destruction to the cost is revealed separately. Thus, it can be analyzed which component affects the economic efficiency of the system more. Each part of a whole is expressed as its third component. This initial phase provides the thermodynamic basis for subsequent economic evaluation. Once the exergy flows, destructions, and losses within the system are identified, the analysis proceeds with an economic assessment based on the total revenue requirement. The total revenue requirement method evaluates the economic performance of an energy conversion system over its entire life cycle, in a manner comparable to Life Cycle Assessment (LCA). Its main objective is to determine the annual revenue that must be generated through product sales to fully compensate all expenditures incurred during operation while ensuring economically sustainable plant performance. The total revenue requirement methodology consists of three main steps:

- Estimation of the total capital investment,
- calculation of the total revenue requirement, including operation, maintenance, and disposal costs,
- and determination of leveled (levelized) product costs (Meyer vd. 2009:180).

All costs incurred from the ownership and operation of each plant component are calculated for each year of the facility's commercial operation with the help of economic assumptions, e.g., type of financing, return on capital, expected inflation rate, federal and state tax rates, investment tax deduction, tax recovery period, book life, annual capacity factor, etc. Then, the cost calculated for each year and for each component is discounted to the present value. This analysis provides the annual flattened cost associated with owning and operating the plant component. These costs include all investment, operation, and maintenance costs associated with component k, as well as an appropriate portion of the overhead costs (Tsatsaronis & Winhold, 1985: 71).

In the next step, the leveled costs are allocated to the system's exergy streams, a process known as exergy costing. Finally, an exergoeconomic evaluation is performed to assess the cost-effectiveness of the overall system and its individual components. This evaluation enables the identification of economically justified improvement potentials based on the relationship between thermodynamic inefficiencies and economic performance (Meyer vd 2009:180).

4. The Relationship Between Exergy Costs and Quality Costs

Cost losses revealed by exergoeconomic analysis based on thermodynamics may not be evaluated within the classical classification of quality costs defined in the literature. Evaluating exergy destruction and related costs in this context requires a deeper physics-based approach. However, considering that energy is the basic and in some cases the highest cost item in the production of products/services by enterprises, the maximum efficiency to be obtained from energy is a phenomenon that enterprises cannot ignore. If quality is defined as no material or resource is wasted, Exergy is the ability of a certain resource to turn into practical work. In this case, exergy destruction can be considered as a loss of quality. This inefficiency and energy waste will be reflected in the form of price increases to customers, who are the most important actors in defining quality.

Taguchi defined that even if the deviation of the determined performance value of the product from the actual performance value remains within the limits of the specifications determined for the product, it is a poor quality. This perspective has opened the door to continuous improvement for us. It has been proven that quality loss can occur even when tolerance values are maintained. From this point of view, every energy that does not turn into practical work is a loss and a waste, even if the system works within tolerance values in its own integrity.

Failure to perform Exergy and exergoeconomic analyses can lead to inefficiencies and irreversibility in the production process, resulting in significant quality costs. This can manifest in the form of increased fuel consumption, higher emission levels, and increased carbon costs in the process. These cost increases can negatively affect the competitiveness and market share of the business by increasing the product prices. In recent years, with increasing social awareness towards environmental pollution and climate change, businesses have been forced to publicly disclose the embedded emissions in the products they produce through sustainability reports. In this context, activities aimed at identifying and reducing the points where irreversibility intensifies in the production system can be considered within the scope of prevention costs as they aim to prevent environmental and economic losses that may occur in the future. Products produced with minimal damage to the environment have been preferred among customers in recent years and serve to ensure customer satisfaction from the Juran point of view. In contrast, penalties and taxes imposed under environmental regulations due to high exergy destruction and unnecessary energy consumption can be classified as failure costs in the quality costs literature.

Within the scope of conducting exergy analysis, evaluating the thermodynamic performance of the system, detecting poor heat transfers, irregular flows, and improper temperature levels requires the employment of qualified engineers. Similarly, the process of assigning costs to exergy streams requires expert knowledge of accounting and financial analysis in exergy economics. In this context, the cost of the expert team formed for analysis and evaluation can be classified as the evaluation cost within the framework of the quality costs literature.

Renovation expenditures resulting from the preference for low-quality equipment in the early investment period and the failure to provide adequate optimization between system components can be considered within the scope of prevention costs if they are aimed at preventing greater efficiency and quality losses that may occur in the future.

5. Conclusion

Traditional cost management techniques, such as total quality management, line rationalization, budget control, cost-volume-profit analysis, standard cost analysis, and process automation, may be limited in identifying hidden costs that arise in production processes. These methods mainly focus on organizational and accounting indicators, and do not directly analyze the physical and thermodynamic properties of machinery, equipment, and processes used in the production process. However, the lack of exergy analysis of a system within the framework of thermodynamic limits leads to high energy and fuel consumption, thus operating with high cost and low efficiency (Uçkan & Ulusoy, 2020: 746). In this study, exergy analysis and the exergoeconomic analysis developed accordingly are positioned as a means of continuous improvement and cost reduction within the scope of the quality costs approach. Associating exergoeconomic analyses with quality costs makes it possible for enterprises to see systemic inefficiencies more clearly and to have an effective decision support tool to prevent or measure and manage these inefficiencies.

Exergoeconomics is a holistic analysis approach that examines a production or service system by decomposing it into sub-components and processes that make up the system, rather than considering it as a single and homogeneous whole. Thanks to this separation, the extent to which each machine, equipment, or process step contributes to the system; on the other hand, it can be clearly demonstrated where exergy destruction, that is, irreversible loss of potential benefit, occurs. Inefficiencies, which often appear at the level of "total expense" or "unit cost" in classical cost analysis, become traceable in terms of the component, physical or operational reason, and the extent of occurrence in the exergoeconomic framework. Thus, bottlenecks caused by low-efficiency machines, excessive energy-consuming processes, incorrect capacity utilization, or design can be clearly identified within the system; it is possible to direct improvement investments not randomly, but to the points with the highest exergy loss and cost burden. At the same time, this approach allows evaluating not only the performance of individual components but also efficiency in terms of the system as a whole, because it can be shown numerically how seemingly small local inefficiencies turn into severe economic losses in total. At this point, exergyeconomics directly intersects with the quality costs approach: the costs associated with exergy destruction are the costs caused by the "poor quality" in the system.

The conceptual model proposed in this study proceeds from the assumption that traditional cost management approaches cannot directly detect thermodynamic inefficiencies in production processes. Exergy analysis quantitatively determines the losses in energy and resource quality by revealing the points where irreversibility is concentrated in the production system. Exergoeconomic analysis, on the other hand, calculates the monetary equivalent of these losses and includes these inefficiencies in the framework of quality costs. Thus, the costs of prevention, evaluation, internal error, and external error; Exergy is associated with destruction and loss, creating a holistic decision support structure for continuous improvement and cost reduction.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Funding Statement

No Fund

Acknowledgments

Authors 1 and 2 contributed equally to this work.

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