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Operational Control Model Based on Integrated Failure Analysis and Risk Assessment in Sustainable Technological Processes

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Abstract: The simultaneous fulfillment of quality, environmental, and occupational safety requirements is a difficult task. The process flow is influenced by numerous factors, and different operational objectives are pursued in different ways. Methodologies reflecting the use of various models, methods, and tools in the integration and implementation of operational goals dedicated to sustainable operation are becoming increasingly important. The subject of the study is an operational control model considering the integrated risk and the steps taken under the conditions of "supervised risk" ensured by the monitoring of the operational criteria. The method was developed for coherent risk management, covering its identification, analysis, assessment, and acceptability estimation in the technological process. The methodology for the assessment, considering the quality, environmental, and occupational safety criteria, and based on the application of the unit risk ratio, allows for the determination of the key operational features, and the methodology of the identification of the key technological parameters applying the integrated risk ratio ensures that the crucial technological parameters are highlighted. The application of the algorithm in the heat treatment process confirms both the effectiveness of the proposed model and the correctness of the thesis: the different requirements set for the technological processes can be simultaneously fulfilled via the application of integrated operational control.

Keywords: process sustainability; operational control and monitoring; integrated risk management; quality, environmental and occupational safety management

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Citation: Karkoszka, T. Operational Control Model Based on Integrated Failure Analysis and Risk Assessment in Sustainable Technological Processes. *Sustainability* **2023**, *15*, 16848. https://doi.org/10.3390/su152416848

Academic Editor: Mirna Habuda-Stanić

Received: 22 August 2023
Revised: 3 November 2023
Accepted: 8 November 2023
Published: 14 December 2023

1. Introduction

The concept of sustainable development involves the implementation of economic and social goals while caring for the natural environment and considering the needs of future generations. Therefore, organizations should function in such a way as to ensure the development of new processes that effectively use raw materials, materials, and human labor, improve the living conditions and safety of people and, at the same time, preserve the sustainability of natural resources. It is crucial that all activities undertaken to implement sustainable development goals have a systemic, repeatable character.

Nowadays, systemic management is one of the basic improvement tools applied by organizations. Within its scope, the repeatability of all actions taken by the organization, a transparent organizational structure, the engagement of all workers, the rational usage of resources, the fluent flow of information and documentation as well and improvement are the determining factors of effective process realization.

It is exactly this systemic approach towards management that today creates the opportunity for considering, within the range of an organization's activities, the requirements of all the clients, workers, and interested parties, which, in turn, may constitute the best way, and the way accepted by all stakeholders, of meeting the quality expectations, increasing work safety and using the environment in a manner that is compatible with sustainable development.

Therefore, it is not surprising that organizations—considering the numerous internal and external benefits that result from introducing the management system and facilitating the fulfillment of the market and institutional requirements—are willing to achieve their normalized guidelines.

Currently, most of the management systems implemented worldwide cover quality, environmental, and occupational safety systems based on the formalized requirements of the ISO 9001, ISO 14001, and ISO 45001 standards. Studies on the skill of simultaneously meeting quality, environmental, and occupational safety requirements, however, confirm that the requirements concerning the realization of benefits, reflecting the operational actions of the company, are the most difficult ones to integrate and undergo at the lowest level [1–7]. Operational aims are realized in a specific way for each independent system appropriate to the various requirements stated by the legal regulations, technical specifications, and application of numerous organizational units [5,8,9]. Very often, in processes, and especially in technological processes, there is a lack of coherence between the operational criteria, which shows the clear need for mastering integration and has resulted in authorial models of management system integration [8,10–12].

The realization of the technological process is determined by numerous factors that determine the fulfillment of the stated requirements via this process. The factors in question, among others, are connected with the control measurement equipment, applied methods, personnel competences, and introduced management system. Theoretically, the technological process should follow the stated conditions; however, in reality, it is accompanied by various threats, which, in turn, result in some probability of incompatibility in fulfilling the agreed-upon integrated aims.

The undertaken method of modeling refrains from the need to integrate aspects of the risks connected with various threats of the planned process realization. The method is directed at the development of an algorithm representing a complex form of description, and the estimation methods and technological risk are performed by the systemic operational control. Thus, the objective of the research was the preparation of an operational control model, including the consistent estimation of the integrated risk and the identification of the operational criteria, dedicated to process realization under the planned conditions of supervised risk.

2. Operational Control

Technological processes are the main elements of production. During technological processes, changes in the shapes, dimensions, and physicochemical properties of the manufactured goods or parts occur, as well as their joining in the units and final goods. Because technological quality is defined by the correct management of the manufacturing process and maintained devices and technological machines, the fundamental meaning of the process belongs to its monitoring. This is applied via measurements of the current values defining the condition of the process or devices, confirmation of the accordance between the obtained values and the accepted criteria, ongoing monitoring allowing for the identification of deregulation in the process, and the control aimed at stabilizing its realization [13–15].

The choice of technological process is determined based on broadly understood economic, social, and ecological criteria and not only on market and technical–organizational ones. The effective management of processes is possible while taking into consideration various criteria while the process management is being realized via, for example, the implementation of management systems and regarding the risk-based approach [13–15].

2.1. Process Approach Based on Risk

Nowadays, the traditional organization structure does not reflect enterprises, which, while functioning in dynamic conditions, must be flexible and adjust their activities to changes that occur [16]. The ability to swiftly react to destabilizing factors can ensure the process approach, according to which "coherent and predictable effects are reached more effectively and efficiently if the activities are understood and managed as the connected with each other processes and which functioning as the coherent ones [17]". This involves the acceptance of the direction towards the management of particular processes, as well as the process management of the organization, which aims to increase the whole-system flexibility via the optimization of its specific processes [18–21].

In every organization process, management plans, organizes, and controls the system of processes and searches for ways to master it. The application of this management concept can be proceeded by the identification and analysis of particular processes [19,22,23], which enables the characterization of all the planned course determinants, especially the input and output factors, process realization criteria, and methods of assessing the compatibility of the realized process and its criteria [22].

Each process is exposed to interfering factors, which results in the need to verify the process's conformity with its criteria, as well as to regulate and improve the process. The mentioned cycle of actions should concern the following [24]:

- The creation, in the process, of the conditions enabling the fulfillment of the requirements;
- Control and assessment confirming that the process is correctly realized and, if there is the need, making corrections and taking corrective actions;
- Improvement focused on increasing the effectiveness of the realized processes.

In processes, changeable environmental conditions create the risk of a lack of conformity with the criteria; therefore, during process planning, it is reasonable to define the risk involved and to ensure the minimization of the influence of the environmental conditions by the process control. In order to manage the processes correctly, planning, control, and improvement that are appropriate to the risk involved should be applied.

The basis of the control mechanisms should constitute the results of the analyses and assessments that are realized with the application of the management tools enabling information processing and concerning the products and processes [25].

Quality process management can cover the following: the development of plans for quality processes and goods, configuration and risk management, goods quality assessment, the production process capability, and the analysis, correction, and mastering of the process and goods parameters. It should also focus on an analysis of the access and used process documentation, the monitoring of the measurement system, the application of the identification and traceability of a system, and device quality estimation. However, the most significant element closing the feedback loop in the quality control process is the use of information concerning the events in the processes while making decisions [26–30].

One should bear in mind that process control—until now interpreted as quality control—will slowly be transformed into the integrated control process, in which the control process is also dedicated to the factors concerning the natural environment and safety, among others. In organizations, the basis of such integration within the range of control is built via the integrated process approach, which guarantees the identification of the process inputs and outputs in the integrated meaning, which is promoted by the following standards: ISO 9001:2015, ISO 14001:2015, and ISO 45001:2018 [1–3]. A stable position can be granted via process control more broadly understood as process management, which measures the preparation level of the organization to effectively realize the processes, including in situations in which there are active disturbing factors in the environment that have impacts on the regular course, is the operational risk together with the systemic requirements.

2.2. Systemic Requirements for Operational Control

The normalized system of management constitutes a standardized set of systemic solutions used by the organization to plan, realize, control, and master its activities in a conscious way. Such a system, in an essential way, regulates behavior, resulting in the fulfillment of the requirements and expectations of external clients, interested parties, and workers while, at the same time, minimizing the risk of not fulfilling the expectations [1–3,8,31]. There are ten chapters covering each of the standards, which refrains from the concept of the management system model named "High Level Structure", the aims of which are to ensure that the common requirements for various management systems are formulated in the same way and that the key definitions and terminologies are unified [32].

Operational control can be defined as the organization's activities concerning these processes, which are related to the quality, environment, and work safety aspects crucial to achieving the quality, environment, and occupational safety aims and are directed toward ensuring conformity within these processes [11,33,34].

Its prototype is operational control with meaningful environmental aspects, which is grounded in the first environmental management system, in accordance with the standard ISO 14001:2004. This environmental management system model refers directly to the operational level via the identification of the environmental impacts as a component of the organization's activities and with a potentially meaningful influence on the environment, as well as the legal requirements regarding the application of these impacts. Operational control ensures that the operations that are connected with the identified and meaningful environmental impacts are realized under monitored conditions [35].

Nowadays, there is a lack of homogenous systemic requirements within the operational control in integrated systems. However, the constant dependence between the approach to running the process and its result is typical not only for the processes realized in accordance with the requirements of the environmental management requirements but also for the ones for which the outcomes of the quality and occupational safety management system requirements are needed. In the current standards, the highest importance, in the context of management on the operational level, is represented by point 8: operational actions, which reflects the realization of the aims that were priorly planned and considers the outcomes of the actions undertaken at the level of planning. The organiza- tion introduces and controls the planned processes by setting the criteria for these processes, ensuring the monitoring of the conditions in the processes, and verifying their compatibility.

There is only one point that, in the range of operational processes, is formally coherent for all the discussed standards: "operational planning and control". It refrains from comparing the standard structures as well as from the directive describing the guidelines for the harmonization of requirements of the different standards prepared by the ISO, including the systemic requirements [32]. This point refers to the implementation of preventive solutions against variations from the planned quality, environmental, and occupational safety aims. The organization should define the criteria of these processes and apply control tools in order to provide the conformity of the processes with the set criteria [1–3].

The requirements included in the ISO system standards do not directly reflect operational control within the scope of integration. These requirements only create the possibility of realizing the processes, which ensures the minimization of the risks connected with incompatibility, environmental influences, and workplace safety outcomes. They represent only the duty of planning and the realization of minimizing the operational risk actions, which are different in different systems. In the context of the various ranges of the operational criteria, organizations at the operational level are again confronted with the problem of how to meet the integrated requirements. Therefore, within this scope, research highlighting effective management methods at the operational level is indispensable, including studies using the risk-based approach.

2.3. Risk Assessment in Operational Control

The risk influences the functioning of each organization: it concerns both the risk understood as the loss threat and the chance of making a profit. Organizations aiming for success should understand the character of the risks "written in" their activities and subsequently implement effective management systems concerning the analysis, assessment, and performance of the activities involved.

The requirement of risk management has been directly written into systemic quality, environmental, and occupational safety management. In each of these cases, the standards require the identification of the organization's risk [36].

Although organizations take advantage of the risk elements of their systemic activities, the norms do not require formalized risk management, nor are there particular methods appointed for its assessment. While applying the rules of risk management within the scope of integrated management systems, organizations may take advantage of the standard ISO 31000 [37], in which the general instructions for risk assessment are similar to the guidelines included in COSO II [38], CAS [39], PN-IEC 62198 [40], and FERMA [41]; thus, they facilitate the interpretation of the threats appearing within the organization, both in the context of entrepreneurship and of the possible losses resulting from not achieving the set aims. In all the mentioned guidelines, the risk assessment covers the following [37–41]:

- Risk identification together with its source;
- Risk analysis, also called risk measurement, allows for highlighting the risk level based on the reason and risk source, the positive and negative consequences of the risk, and the probability that these consequences will occur;
- Risk assessment by comparing the risk assessment outcomes with the accepted criteria of risk acceptability.

As a result of the risk assessment, the organization makes decisions connected with priority actions from the point of view of risk management.

While managing the risk, management should consider that the daily activities of the organization are connected with only some of the outcome probabilities regarding the threats to achieving the aims in the technological processes. Therefore, the best approach to technological risk-taking is the systemic management of the risk, aimed at preventing the outcomes of quality, environmental, and occupational safety threats by ensuring safety and reliability in processes [36].

2.4. Multi-Criteria FMEA

Operational control, based on risk assessment and having a systemic character, is aimed at ensuring safety and reliability in processes.

Safety in processes should be created by systems in which technical, technological, and organizational solutions are implemented, and which ensure the safe realization of the processes and prevent losses. Safety in processes is aimed at preventing losses within the scope of workers' health and the environment, losses resulting from breaking the process continuity, and, finally, material losses of the enterprise [34,42]. Safety can be described as "the freedom from unacceptable risk of physical injury or of damage to the health of people, either directly, or indirectly as a result of damage to property or the environment [43]".

The safety system aims to prevent the occurrence of dangerous events and other threats, as well as to minimize their effects, to realize the functional goals [34]. A further aim of the safety system is to avoid unforeseen situations and failures in functionality, which can be caused by environmental influences, health problems, and financial losses [44]. The safety system should be created as an integral part of the functional system, or it should be added from the outside [45–47].

Reliability in the context of process safety is commonly associated with the functional system of the organization, consisting of machines, devices, and human factors, thanks to which technical objects can fulfill their designed functions. Reliability can be defined as the "probability that a machine will perform its required functions without failure for a specified time period when used underspecified conditions [48]", or as the "probability that an item can perform its intended function for a specified interval under stated conditions [49]".

Thus, safety in processes must ensure the reliability of the items of both the functional and safety systems. To predict operational problems and ensure a failure-free performance, it is necessary to define and assess the risk involved [50,51].

The basic methods that have been used for many years in the assessment and optimization of the failure rate of the entire system and its components are as follows [52–57]:

reliability block diagrams (RDBs), fault tree analysis (FTA), failure modes and effects analysis (FMEA), event tree analysis (ETA), and Markov models and Monte Carlo simulation, which are used alone or in combination. Failure modes and effects analysis (FMEA) is often an essential component.

Failure modes and effects analysis (FMEA) was developed in the U.S. in the 1950s with the original purpose of preventing defects in products at the design stage for military, aerospace, and aviation applications. Today, it is used in every industry to identify product and process problems, eliminate failures, prevent defects, and plan controls [58–60].

FMEA involves identifying nonconformities, determining the cause-and-effect relationships, calculating the risk priority number (PRN), and taking actions appropriate to the values of these indicators and aimed at improvement. The risk priority number depends on the probability of the occurrences of defects and their significance and detectability.

It should be emphasized that the purpose of FMEA is to prevent a situation in which the requirements are not met. Thus, the analysis can be aimed not only at quality criteria, but also at environmental, safety, cost, and performance criteria, among others [61].

Within the range of FMEA applications, there are no recommended methods to identify and assess the expected failures, nor are there recommendations for the identification of the potential measurement parameters that indicate the presence or occurrence of the faults, which is why organizations choose the tools that they use based solely on their own needs. Moreover, they develop and apply authorial methods dedicated to the processes they carry out. These new methodologies include the following:

- The integration of failure mode effects and criticality analysis (FMECA) and ANP (analytic network process), splitting the severity, occurrence, and detectability into sub-criteria, arranging them in a hybrid decision structure for including qualitative judgments and reliable quantitative data in the analysis and incorporation of the consequences of the domino effects in the criticality assessment [62];
- Improvement in the Sphynx method, including the application of product tree (PT), safety block diagrams (SBDs), preliminary hazard analysis (HPA), functional analysis (FA), functional failure mode effects and criticality analysis (FMECA), safety targets (STs) corrected by new factors of safety allocation (environmental danger/functionality factors) and the integrated hazard method, which ensures better flexibility [63,64];
- Changing the Sphynx method by proposing critical allocation and catastrophic allocation factors within the range of the mathematical formulation of the new safety allocation technique: the integrated dangers method [65];
- The modification of failure mode and effects and criticality analysis (FMECA) via the introduction of prevention, effectiveness, and cost factors, and the formulation of a new methodology with a new total efficient risk priority number (TERPN) [66,67];
- The unification of the occurrence, severity, and detection grades in the assessment of the safety, environmental, and quality risks in the application of failure mode and effects analysis (FMEA) [68];
- The integration of quality, environmental, and occupational risk assessment methods based on failure mode and effects analysis (FMEA) and the inclusion of additional factors: the difficulty in realizing the technological parameters, their influence on the fulfillment of the requirements, and the importance of the requirements in the risk assessment [69];
- The modification of the conventional failure mode and effects analysis (FMEA) via the application of anticipatory failure determination (AFD) in the identification of the possible failures and analytic hierarchy process (AHP) in the calculation of the weight of the risk priority number (RPN) factors [70];
- Improvement in the classic failure mode and effects analysis (FMEA) via the utilization of the cloud model (CM), calculation weights using the interval analytic hierarchy process (IAHP), and the introduction of the cloud risk priority number (CRPN) [71];
- The combination of prospect theory (PT) and failure mode and effects analysis (FMEA) via the introduction of the relationship between the occurrence, severity, and detectabil-

ity factors of the risk priority number (RPN) and the main principles of prospect theory [72];

- The application of the interval-valued Pythagorean fuzzy number (IVPFN) with the Bonferroni mean operator and the interactive multi-criteria decision-making (MCDM) approach for the determination of the risk priority numbers in failure mode and effect analysis (FMEA) [73];
- The unification of the quality, environmental, and occupational safety approaches for risk analysis via the application of machinery and process failure mode and effects analysis (FMEA) [74].
- The literature indicates numerous studies on the modification of FMEA and its application to various processes independently based on different criteria. These modifications are specifically aimed at reducing the uncertainty in the evaluation process. FMEA is rarely used to determine risks arising simultaneously from quality, environmental, and safety factors.

3. The Operational Control Model

3.1. Aims of the Study

In sustainable technological processes, there is a clear tendency towards their optimization, including not only the technical but also the environmental and occupational safety aspects. This implies the need to use methods for the assessment and implementation of operations that consider the integrated quality environmental, health, and safety requirements and that prevent the occurrence of the effects of their threats in the process. Taking into account considerations in the literature and the results of preliminary research, the following thesis was formulated: in technological processes, quality, environmental, and occupational safety requirements can be fulfilled sustainably through the application of integrated operational control.

This thesis assumes that it is possible to realize any technological process within the scope of achieving the operational goals of the organization under the conditions of supervision (operational control), which, at the same time, prevents the occurrence of defects and negative impacts on the environment and employees.

This study considers the most important factors that affect the technological process from the point of view of minimizing the integrated risk of the technological process.

The objectives of the study are described as follows:

- The preparation of a consistent method of identification, analysis, assessment, and acceptability estimation of the integrated risk in the technological process, taking into account the quality, environmental, and safety criteria;
- The development of a method that enables the definition of the key operational parameters and their criteria, considering the criterion of integrated risk and allowing for the realization of processes in pre-planned conditions of supervised risk.

The integrated risk method builds on failure mode and effects analysis (FMEA). The novelty of the method is that it considers the quality, environmental, and safety criteria in a unified manner and allows for a clear determination of the integrated risks of a process. Awareness of the integrated risks is the foundation of actions aimed at reducing them while considering various criteria. The operational criterion method is entirely original. The contribution of the method is that it ensures that various operational goals dedicated to sustainable operations can be simultaneously identified and achieved.

Practical ways of applying operational control in selected heat treatment operations are described in the context of quality, environmental, and occupational safety, as they have been an area of long-term interest for the author.

3.2. Original Operational Control Methodology

3.2.1. Integrated Risk Assessment

The developed original method of the integrated risk assessment of a technological process assumes that the realization of the process directly affects the formation of potential defects, environmental impacts, and the effects of occupational threats.

When taking advantage of the flexibility of the tools and methods of quality assessment, environmental impact assessment, and occupational risk assessment, as well as the common idea of continuous improvement in integrated management systems, it is advisable to use an algorithm for the simultaneous assessment of non-compliance. The algorithm's development was based on the assumption that the potential causes of defects, environmental impacts, and occupational effects are lower-order elements that do not meet their functions, and the defects, environmental impacts, and occupational effects are higher-order elements that do not meet their functions.

Quality has been defined as the "degree to which a set of inherent characteristics of an object fulfills requirements", and the defect has been defined as the "non-fulfillment of a requirement related to an intended or specified use [17]".

The environmental aspect has been defined as the "element of an organization's actions or products or services that can interact with the environment [2]", and the environmental impact has been described as "any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects [2]".

An occupational safety threat has been characterized as a "source with a potential to cause injury or ill health [3]" while indicating an occupational injury or disease as a consequence of the threat.

The proposed algorithm for the simultaneous assessment of defects, environmental impacts, and the effects of threats to the health and life of employees, preceded by integrated process identification, includes the following:

- The identification and characterization of the defects, environmental impacts, and effects of occupational safety threats and their causes;
- An assessment of the significance and probability of the occurrence of defects, environmental impacts, and effects of occupational safety threats by assigning priority numbers;
- An assessment of the risks related to the presence of defects, environmental impacts, and the effects of occupational safety threats;
- The selection of processes characterized by high values of the risk ratios of defects, environmental impacts, and effects of significant safety threats.

The results of the identification of the defects, environmental impacts, and occupational safety effects in the technological process form the basis for the assessment of the integrated risk.

The quality risk is defined as the function of the probability of the occurrence of the defect, the significance of the defect, and the possibility of its control. It is estimated via the priority number of the occurrence of the defect (PROq), the priority number of the defect significance (PRIq), the priority number of the control (PRCq), and, in effect, the unit quality risk ratio (URRq), expressed as Equation (1):

$$\mathrm{URRq} = \mathrm{PROq} \times \mathrm{PRIq} \times \mathrm{PRCq} \quad (1)$$

where URRq is the unit quality risk ratio; PROq is the priority ratio of the defect occurrence; PRIq is the priority ratio of the defect importance; PRCq is the priority ratio of the defect control.

The criteria to define the priority ratio of the defect occurrence (PROq)—defining the frequency of the occurrence of quality nonconformities—are compared in Table 1.

The criteria for estimating the priority ratio of the defect importance (PRIq) are compiled in Table 2.

The criteria that are indispensable for defining the priority ratio of defect control (PRCq)—considering all the applied preventive actions—are compiled in Table 3.

Table 1. List of criteria to estimate the frequency of defect occurrence—PROq.

PROq	Estimation Criteria
1	Isolated situations of defect occurrences linked to the same or similar processes; the process is statistically capable: Cp > 1.00, P < 0.27%.
2	Rare cases of defects that accompany the same or similar processes; low probability of the occurrence of the defect's source; the process is statistically stable: Cp $\leq$ 1.00, P $\geq$ 0.27%.
3	The defects accompany the same or similar processes; the source of the defect occurs occasionally; the process is still under statistical control: P $\approx$ 5%.
4	Frequent cases of defect occurrences; the source of the defect is repetitive; the process is beyond statistical control: 12.5% < P < 50%.
5	The existence of defects is almost or totally unavoidable; P $\approx$ 50% $\div$ 100%.

Table 2. List of criteria for the defect importance assessment—PRIq.

PRIq	Estimation Criteria
1	A slight defect that does not have any real effect on the operation of the system or affect the course of the technological process or operation.
2	Low defects cause only slight dissatisfaction of the operator, slight deterioration in the system's performance, or necessary slight changes in the technological process.
3	The defect causes some dissatisfaction, discomfort, or nervousness in the operator regarding the occurrence of the defect.
4	Defects result in a high degree of operator dissatisfaction and are likely to cause serious disruptions in subsequent technological operations, requiring large modifications.
5	Defects affecting the safety of the operation of the system or legal provisions.

Table 3. List of criteria to estimate the defect control—PRCq.

PRCq	Estimation Criteria
1	The control activities will almost certainly detect the existence of defects; the process automatically highlights the defect; and the cause of the defect will certainly be detected.
2	The control activities have a high chance of detecting the existence of the defect; the detection of the cause of the defect is very likely; the control tests are certain, independent of each other.
3	The control activities allow for the detection of existing defects; the detection of the cause of the defect is probable; relatively reliable test.
4	The control activities have a low chance of detecting the defect; the detection of the cause of the defect is unlikely and presumably cannot be detected; tests are uncertain.
5	The control activities do not allow for the detection of the defect; the detection of the cause of the defect is impossible; the cause of the non-compliance has not or cannot be investigated.

In the model of operational control, the high values of the unit quality risk ratio (URRq) indicate the key defects and need to be subjected to operational monitoring. The key character is also reflected in priority ratios of the defect occurrence, importance, and control (PROq, PRIq, PRCq) of high values. The sum of the values of the unit quality risk ratio (URRe) of all the identified defects reflects the entire quality risk of the analyzed process.

The environmental risk is defined as the function of the probability of the occurrence of environmental impacts, the significance of the impacts, and the possibility of control. This risk is estimated via the priority numbers of the occurrence of environmental impact (PROe), the impact significance (PRIe), the control (PRCe) and, in effect, the unit environmental risk ratio (URRe), expressed as Equation (2):

$$URRe = PROe \times PRIe \times PRCe \quad (2)$$

where URRe is the unit environmental risk ratio; PROe is the priority ratio of the environmental impact occurrence; PRIe is the priority ratio of the environmental impact importance; PRCe is the priority ratio of the environmental aspect control.

The criteria essential to characterize the priority ratio of the environmental impact occurrence (PROe)—describing the frequency of the occurrence of the environmental aspect outcome considering all the applied preventive actions—are compiled in Table 4.

Table 4. List of criteria to estimate the occurrence of environmental impacts—PROe.

PROe	Estimation Criteria
1	Environmental impact occurrence is improbable; there have never been any environmental aspects or impacts related to the same or similar processes.
2	There is little probability of environmental impact occurrence; the rare and temporary cases of environmental impact occurrence are linked with the same or similar processes.
3	Environmental impact occurrence is probable; there have been environmental impact situations.
4	Environmental impact occurrence is highly probable; there have been situations of numerous and long-lasting environmental impacts.
5	Environmental impact occurrence is unavoidable; environmental impacts are always present.

The criteria to estimate the values of the priority ratio of the environmental impact importance (PRIs) are compiled in Table 5.

Table 5. List of criteria for environmental impact importance assessment—PRIe.

PRIe	Estimation Criteria
1	Unimportant in the context of area, quality, and quantity; environmental pollution: an almost immediate return to the initial balance condition.
2	Area-insignificant environmental pollution; environmental imbalance that is naturally reversible within a short period of time following the environmental impact occurrence.
3	Area-significant environmental pollution; environmental imbalance that is reversible only due to the intervention of humans.
4	Environmental pollution in the contexts of the amount, quality, and area-importance; is severe environmental degradation that is reversible only due to the heavy intervention of humans.
5	Area-significant, total environmental degradation.

The criteria indispensable for defining the priority ratio of the environmental aspect control (PRCe)—reflecting the supervision over the environmental aspect, considering all the steps taken for its control and supervision—are compared in Table 6.

Table 6. List of criteria to estimate control of environmental aspect—PRCe.

PRCs	Estimation Criteria
1	The environmental aspect is under constant control, detected automatically, and subjected to supervision.
2	The environmental aspect is under constant control and subject to supervision.
3	The environmental aspect is under poor control and there is little or no chance of its supervision.
4	The environmental aspect is hardly ever controlled or is not subjected to any control actions; the control actions are of low effectiveness; the aspect is barely supervisable.
5	The environmental impact is beyond the control actions; there are no measures to detect the impact; the environmental aspect is unsupervisable.

In the model of operational control, high values of the unit environmental risk ratio (URRe) indicate that the environmental impact has a key character and needs to be subjected to operational monitoring. The key character is also reflected in environmental impact and impact occurrence, importance, and control (PROe, PRIe, PRCe) priority ratios of high values. The sum of the values of the unit environmental risk ratio (URRe) of all the identified environmental impacts reflects the entire environmental risk of the analyzed process.

The occupational risk is defined as the function of the probability of the occurrence of the occupational threat effect, the significance of the occupational effect, and the exposure to the threat. It is estimated via the priority numbers of the occurrence of the occupational threat effect (PROs), its significance (PRIs), the exposure (PREs) and, finally, the unit occupational risk ratio (URRs), expressed as Equation (3):

$$\mathrm{URRs} = \mathrm{PROs} \times \mathrm{PRIs} \times \mathrm{PREs} \quad (3)$$

where URR is the unit occupational risk ratio; PRO is the priority ratio of the occupational threat effect occurrence; PRI is the priority ratio of the occupational threat effect importance; PRE is the priority ratio of the exposure to the occupational threat.

The criteria essential for the definition of the priority ratio of the occupational threat effect occurrence (PROs)—characterizing the frequency of the occurrence of the occupational safety threat outcomes and including all the applied preventive actions—are presented in Table 7.

Table 7. List of criteria to estimate the occurrence frequency of injuries and occupational illnesses—PROs.

PROs	Estimation Criteria
1	Near improbability for the occurrence of injuries and occupational illnesses, occupational accidents, or disease that appear at a maximum of twice during the worker's labor activity.
2	Low probability for the occurrence of injuries and occupational illnesses; the incapacity to work (from the effect of the workplace safety threat) can occur at a maximum of twice over 5 years during the worker's labor activity.
3	Moderate probability for the occurrence of injuries and occupational illnesses; the incapacity to work (from the effect of the workplace safety threat) can occur once every 2 years during the worker's labor activity.
4	High probability for the occurrence of injuries and occupational illnesses; incapability of work (effect of the workplace safety threat) can occur at a maximum of twice per year during the worker's labor activity.
5	Very high probability for the occurrence of injuries and occupational illnesses; the incapacity to work (effect of the workplace safety threat) can occur more than once a month during the worker's labor activity.

The criteria for estimating the priority ratio of the occupational threat effect importance (PRIs) are compared in Table 8.

Table 8. List of the criteria for assessment of the injury and the occupational illnesses importance—PRIs.

PRIs	Estimation Criteria
1	Ailments not affecting the capacity to work; fatigue; hardly harmful.
2	Occupational injuries and diseases causing short-term ailments and not affecting the capacity to work: eyesight irritation; poisonings; cuts; headaches; hardly harmful.
3	Occupational injuries and diseases causing short-term and repeating ailments, affecting the capacity to work in the short term: bruises; skin allergies; uncomplicated fractures; first-degree burns; second-degree burns on small areas; wounds; moderately harmful.
4	Occupational injuries and diseases causing heavy and continuous ailments, affecting the long-term capacity to work: strong third-degree burns; second-degree burns on large body areas; damage to or loss of eyesight or hearing; black lung; asthma; fractures with dysfunction; vibration white finger syndrome; highly harmful.
5	Occupational injuries and diseases causing heavy and constant ailments, contributing to the full incapacity to work: amputations; multi-area fractures with dysfunction; toxic harms of the nervous system and internal organs; injuries and illnesses with the consequence of the death of one or more person; neoplastic diseases; extremely harmful.

The criteria that are necessary for defining the priority ratio of the occupational threat exposure (PREs)—representing the frequency of the exposure of the worker to threats taking into account the preventive actions—are compiled in Table 9.

Table 9. List of criteria to estimate exposure of workers to threats—PREs.

PREs	Estimation Criteria
1	Rare: once a year
2	Minimal: several times a year
3	Sporadic: once a month
4	Common: more than once a week
5	Continuous: every day

High values of the unit occupational risk ratio (URRs) indicate the occupational key threats and need to be subjected to operational monitoring. The key character of threats is also reflected in occupational threat occurrence, importance, and exposure (PROs, PRIs, PREs) priority ratios of high values. The sum of the values of the unit occupational risk ratio (URRs) of all the identified occupational threats reflects the entire occupational risk of the analyzed process.

The achievement of the quality, environmental, and occupational goals, dependent on the implementation of the technological parameters, is reflected by the integrated risk ratio (IRR), which considers the impact of the implementation of the technological parameters on ensuring the specified requirements in terms of quality, environmental, and occupational safety. The impact of the implementation of the technological parameters on the provision of the operational features is defined as the degree of support, and its strength is characterized as present (+) or absent (−).

The value of the integrated risk ratio (IRR) for every technological parameter is the sum of the products of the values of the unit risk ratios for individual technological features (URR) and their degrees of support (I) with a specific operational criterion (4):

$$IRR = \sum_{i=1}^{n} \mathrm{I} \times \mathrm{URRi} \quad (4)$$

where IRR is the integrated risk ratio fulfilling quality, environmental, and occupational safety requirements dependent on the implementation of the technological parameters; URRi is the unit risk ratio associated with the occurrence of a defect, environmental impact, or occupational threat in the process; I is the degree of support describing the relationship between a specific technological parameter and specific technological feature.

The unit risk ratio (URRi) reflects the risk associated with individual non-compliance. It may describe the risks associated with the defect occurrence reflected by the unit quality risk ratio (URRq), the environmental impact described by the unit environmental risk ratio (URRe), or the occupational threat effect characterized by the unit occupational risk ratio (URR).

Each technological parameter may have an impact on the formation of defects, environmental influences, and effects of occupational safety threats, as well as on the risks connected with them. It may be that a specific technological parameter only has an impact on the formation of defects and does not affect the environment or occupational safety threat effects. It is possible that the maintenance of a technological parameter determines the existence of all types of incompatibilities.

This effect of a specific technological parameter on the existence of specific incompatibilities is defined as the degree of support that describes the relationship between a specific technological parameter and a specific technological feature (I), and it can be determined as the presence (+) of the relationship, which has a value of 1.

The integrated risk ratio (IRR) values indicate the technological parameters that are important for obtaining the planned quality and environmental and occupational safety features. Technological parameters described by high IRR values are of crucial importance in operational control and require special supervision.

3.2.2. Operational Monitoring

Monitoring—in accordance with the developed risk assessment methodology in the integration scope—may be subjected to the values of the unit quality risk ratio (URRq), unit environmental risk ratio (URRe), and unit occupational risk ratio (URRs) for individual defects, environmental impacts, and effects of occupational safety threats. Information in monitoring can also represent high values of the priority ratios of occurrence (PRO), importance (PRI), and exposure (PRC(E)).

Operational monitoring is defined in the operational control model as the identification of operational criteria, the determination of the optimal values for them, and verification to confirm the compliance between the operational criteria and optimal values. Such activities are ultimately aimed at meeting legal requirements, technical specifications, and other requirements of interested parties.

The operational criteria refer to the crucial operational parameters of the process that are the direct subjects of the monitoring.

The operational parameters should be understood as the technological parameters or features that can be either directly or indirectly monitored.

The key operational parameters have been described, which, due to the high value of the risk ratio, have a decisive impact on meeting the requirements of stakeholders.

The starting point for defining the operational criteria is the identification of the key operational parameters.

A scheme of operational control including the identification and verification of the operational criteria under operational monitoring is shown in Figure 1.

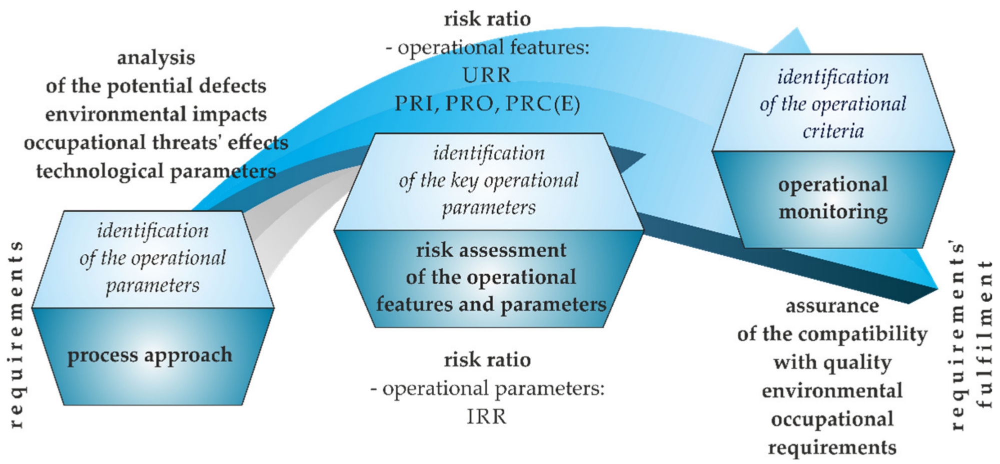

Figure 1. Scheme of operational control.

Monitoring, in accordance with ISO 9000:2015 (point 3.11.3), means "determining the status of a system, a process, a product, a service, or an activity", and, in accordance with point 3.4.8 of ISO 14001:2015 and point 3.28 of ISO 45001, "determining the status of a system, a process or an activity", using verification, supervision and critical observation [14,28,29].

The definition of operational criteria must be preceded by a description of all the operational parameters affecting the fulfillment of the integrated requirements and an indication of the factors that determine their implementation to a significant extent. Therefore, the operational parameters are identified first, which include not only the technological parameters but also the formulated requirements for the products, environmental impact, and occupational safety. These parameters are subjected to an assessment, the basic element of which is the risk accompanying the process. Thus, the importance of the operational parameters is determined by the values of the following ratios:

- The unit risk (URRq, URRe, URRs), which describes the risk associated with the occurrence of defects, environmental impacts, and occupational safety threat effects;
- The integrated risk (IRR), which characterizes the impact of specific technological parameters on fulfilling the integrated requirements.

The use of risk ratios makes it possible to identify the operational parameters that are of key importance for meeting the requirements (i.e., those that must be monitored). In reality, the operational parameters are part of the operational monitoring. The need to indicate operational criteria results from the specificity of the monitored process. The operational parameters may not always be directly monitored while being at the same time the operational criteria. In some cases, the subject of the monitoring must be an intermediate parameter, for which compliance with the requirements is tantamount to meeting the requirements of the operational parameter.

The operational criterion is the parameter that determines the optimal value and that, for practical reasons, can be verified in the process.

The operational parameters indicated as the key ones may not always be directly subjected to monitoring because there is no technical or organizational possibility of verifying them. In this case, it is necessary to set operational criteria for them, which should be monitored. Therefore, an operational criterion can be an operational parameter, or it can be another factor reflecting the operational parameter. Determining the optimal and critical values of the operational criteria and the methods of monitoring them, and indicating the persons responsible for maintaining the operational criteria at the optimal level, enable a stable implementation of the technological process from the perspective of obtaining the assumed parameters of the manufactured products, as well as the impact of the monitored processes on the environment and employees.

Therefore, the indication of the key technological parameters and features determines the identification of the operational criteria, while supervision over the operational criteria ensures the compliance of the key technological parameters and features with the requirements.

4. Application in Heat Treatment Operations

Heat treatment is a technological process that results in changes in the mechanical and physical properties of metals and their alloys in the solid state. Structural changes during heat treatment are a function of temperature and time, as well as—in some cases—the environment, plastic deformation, or the magnetic field [75]. In practice, the technological process is most often carried out as heat treatment in annealing, hardening, tempering, and precipitation-strengthening operations, as well as surface treatment and thermal–chemical treatment [76,77].

In the analyzed technological process, heat treatment is carried out as volumetric hardening. The hardening operation consists of heating to the austenitizing temperature, soaking at this temperature, and cooling down at a rate ensuring the obtainment of a martensitic or bainitic structure. It is carried out in chamber furnaces and quenching tanks filled with quenching oil. The process is influenced by many factors, the presence of which may result in defects in the material undergoing the heat treatment. The furnace used is an electrical device; therefore, the environmental impacts primarily result from maintaining a high temperature and electricity consumption. The use of oil in cooling down the charge and oily wastewater during washing is also important. Particular threats to work safety are the application of high-temperature oil and direct contact with hot elements and moving devices.

An integrated risk assessment was carried out using the prepared methodology. The identification and assessment of the technological features within the quality, environmental, and occupational range included defects/environmental impacts/occupational threats, as well as their effects and potential causes (PRI/PRO/PRC(E)/URR). The identified non-compliances mostly include the following:

- A structure different from the planned one (partial lack of hardening effects); insufficient hardness of the hardened steel; a heating temperature that is too low and/or a heating time that is too short; too low cooling rate from the austenitization temperature—4/1/3/12;
- An overheated, coarse structure; deterioration in mechanical properties; a heating temperature that is too high and/or a heating time that is too long—3/1/3/9;
- A structure locally different from the planned structure; "soft spots" with low hardness (uneven hardness); the improper surface preparation of workpieces—3/2/3/18;
- The oxidation of the surface; increasing the hardness of the surface layer; deterioration in the mechanical properties; failure to comply with the planned parameters of the protective atmosphere or its absence—5/1/3/15;
- Surface decarburization; a reduction in the surface layer hardness; deterioration in the strength properties; failure to comply with the planned parameters of the protective atmosphere—3/1/3/9;
- Temperature stresses; cracks, deformations, twists, warping, buckling; a heating rate that is too high; uneven heating; a heating temperature that is too high; a cooling rate that is too high; different cooling rates for different surfaces of the heat-treated workpiece; incorrect arrangement in the furnace—5/3/5/75;
- Electricity intake; decrease in natural resources; heating operations; heating of the washing bath; the drive of lifting and transport equipment; the agitator and cooler of the hardening bath; chamber washer—5/5/1/25;
- Water intake; the exhaustion of natural resources; the cooling of the hardening bath; the use of a spray washer; the washing of machinery and equipment—5/5/1/25;
- Industrial wastewater containing quenching and hydraulic oils, emulsions, and lubricants; the pollution of surface water, groundwater, and land; the use of a spray washer; the washing of machinery and equipment—5/3/1/15;
- Hazardous waste: used quenching and hydraulic oils; soil and groundwater contamination; taking up space in landfills; the consumption and replacement of quenching and hydraulic oils—4/3/2/24;
- Hazardous waste: oily wipes, sawdust, and sand; soil and groundwater contamination; taking up space in landfills; the removal of oil and grease during equipment repairs and possible leaks—4/3/2/24;
- Hazardous waste: oils and lubricants separated from "dirty" sewage; soil and groundwater contamination; taking up space in landfills; the separation of oils and lubricants from "dirty" wastewater in contact with the processed material and used equipment—4/3/2/24;
- Non-hazardous waste: scrap; occupying area in the landfill until recycling; the manufacturing of non-compliant products; the wear of machine and equipment components; the scrapping of equipment and machines—1/3/2/6;
- Risk of industrial accident (hardening oil); uncontrolled soil, surface, and groundwater contamination; faulty operation of equipment and installation; the use of technical solutions conducive to the occurrence of danger; poor technical conditions of equipment and installation—5/1/1/5;
- Contact with extremely high-temperature objects; death due to first-, second- and third-degree skin burns; temporary or permanent eyesight injury; high temperatures in the quenching furnace; the high temperature of the oil bath—5/1/4/20;
- Hot working conditions leading to the overheating of the body and loss of consciousness; high temperatures in the quenching furnace; the high temperature of the oil bath—2/3/5/30;
- Contact with "oil mist" leading to headaches and dizziness and chronic acute poisoning; the evaporation of oil from the quenching bath—2/2/4/16;
- Skin and eye contact with chemicals leading to damage and inflammation of the skin, mucous membranes, and eyes; the release of acrolein during the thermal de-

composition of quenching oil; the use of the alkaline salt solution in the surface preparation—3/2/4/24;
- Contact with sharp, protruding, and rough surfaces causing bruises and cuts, mainly limb, head and hand abrasions; the operation of heat treatment furnaces and other equipment; passages in the hardening plant—2/2/4/16;
- Contact with moving elements of machines and devices leading to bruises and head injuries; the operation of machines and devices—3/2/4/24;
- Material falling onto the legs resulting in bruises, fractures, and crushes; manual material handling—3/1/3/9;
- Slipping and falling on the same plane leading to limb fractures and sprains, body contusions, and head injuries; uneven and slippery surfaces in the hardening plant—3/1/3/9;
- Overload of the musculoskeletal system resulting in diseases and injuries of the musculoskeletal system and hernia; lifting, moving, and repeating actions—3/1/2/6;
- Working in a standing position resulting in diseases of the musculoskeletal system; the operation of supporting machinery and devices—2/1/5/10;
- Noise exposure resulting in momentous or permanent hearing loss; the operation of supporting machinery and devices—2/1/5/10;
- Stress resulting in the diminishment of the psychical and mental efficiencies, hearing, eyesight, manual precision efficiency, and illness defense; an overly high pace of work; three working shifts requiring quick response times and high levels of responsibility—3/3/3/27;
- Risk of industrial accident (fire, explosion), such as heavy burns all over the body or strong poisoning, which can possibly lead to death; the implementation of heating and cooling at high temperatures—5/1/4/20.

Defects, environmental impacts, and occupational safety threats of the key character have been indicated, taking into account the maximum values of the priority ratios and maximum values of the unit risk ratios, calculated on the bases of Equations (1)–(3), which are higher than those considered acceptable and are summarized in Table 10.

The maximum values of the priority ratios for the analyzed process are characterized as PRO/PRI/PRD(E) = 5. The maximum value of the unit risk ratio was defined at the level of URR $\geq$ 24.

The key technological features were identified via high unit risk ratio values, higher than those described as the maxima.

In terms of meeting the quality requirement as defects, which is described by the highest value of the unit quality risk ratio, thermal stresses are qualified (URRq = 75).

In terms of meeting the environmental requirements, the highest values of the unit environmental risk ratio are indicated for the following:

- Electricity consumption (URRe = 25);
- Water consumption (URRe = 25);
- Hazardous waste in the form of used hardening and hydraulic oils (URRe = 24);
- Hazardous waste in the form of oily wipes, sawdust, and sand (URRe = 24);
- Hazardous waste in the form of oils and lubricants separated from "dirty" sewage (URRe = 24).

In terms of meeting the occupational safety requirements, the important effects result from the following:

- High temperatures at the workplace (URRs = 30);
- Exposure to stress (URRs = 27);
- Skin and eye contact with chemicals (URRs = 24);
- Contact with moving elements of machinery and equipment (URRs = 24).

The key importance of the technological features was also determined via the critical occurrence (PRO), significance (PRI), and detectability or exposure (PRC(E)). On this basis, the following are considered to be the key technological features:

- In the field of quality assurance: thermal stress (PRIq = 15) and surface oxidation (PRIq = 5);
- In the environmental range: the consumption of electricity (PRIe = 5, PROe = 5) and water (PRIe = 5, PROe = 5) and the risk of failure resulting from the use of quenching oil (PRIe = 5);
- In the field of occupational safety: work in microclimatic conditions (PREs = 5), in a standing position (PREs = 5), and with noise exposure (PREs = 5), and the risk of failure resulting from potential fire conditions (PRIs = 5).

The key technological parameters were determined using the integrated risk ratio (IRR), based on Equation (4). The IRR values are dependent on the values of the unit risk ratios (URRq, URRe, URRs) and the degree of support determining the presence (1) of relationships between the individual technological features and the technological parameters determining them. An exemplary dependency matrix to indicate the key technological parameters in the hardening operation is presented in Table 11.

Table 10. List of key technological features in hardening operations.

Key Technological Features	Determinants of Key Character	
	URRq/URRe/URRs	**PRO/PRI/PRD(E)**
Oxidation of the surface	-	PRIq = 5
Thermal stresses	URRq = 75	PRIq = 5
Electricity intake	URRe = 25	PRIe = 5, PROe = 5
Water intake	URRe = 25	PRIe = 5, PROe = 5
Industrial wastewater containing quenching and hydraulic oils, emulsions, and lubricants	-	PRIe = 5
Hazardous waste: used quenching and hydraulic oils	URRe = 24	-
Hazardous waste: oily wipes, sawdust, and sand	URRe = 24	-
Hazardous waste: oils and lubricants separated from "dirty" sewage	URRe = 24	-
Risk of industrial accident: hardening oil	-	PRIe = 5
Contact with extremely high-temperature objects	-	PRIs = 5
Hot working conditions	URRs = 30	PREs = 5
Skin and eye contact with chemicals	URRs = 24	-
Contact with moving elements of machines and devices	URRs = 24	-
Working in a standing position	-	PREs = 5
Noise exposure	-	PREs = 5
Stress	URRs = 27	-
Risk of industrial accident: fire, explosion	-	PRIs = 5

In the hardening operation, the values of the integrated risk ratio were calculated as follows:

- IRR = 171 for the washing-bath parameters;
- IRR = 351 for the austenitizing temperature;
- IRR = 326 for the heating time and IRR = 264 for the cooling rate;
- IRR = 30 for the composition of the protective atmosphere.

The integrated risk ratio (IRR) values that determine the key character of the technological parameters cannot be clearly defined. They depend on both the type of process and, in particular, on the magnitude of the quality, environmental, and occupational safety risks that accompany it, as well as on the stage of the development of the process in the context of its possible improvement. The maximum value of the integrated risk ratio for the analyzed process has been described at the level of IRR $\geq$ 300.

Table 11. Matrix of dependences between unit risk ratio (URR) and integrated risk ratio (IRR) values: 1—parameters of washing baths; 2—austenitizing temperature; 3—heating time; 4—cooling rate; 5—composition of protective atmosphere.

Technological Features	**URR**	**Technological Parameters**				
		1.	**2.**	**3.**	**4.**	**5.**
Structure with partial lack of hardening effects	12		+	+	+	
Overheated, coarse structure	9		+	+		
Structure with “soft spots” of low hardness	18	+				
Oxidation of the surface	15					+
Surface decarburization	9					+
Temperature stresses	75		+	+	+	
Electricity intake	25	+	+	+	+	
Water intake	25	+	+			
Industrial wastewater containing quenching and hydraulic oils, emulsions, and lubricants	15	+				
Used quenching and hydraulic oils	24		+	+		
Oily wipes, sawdust, and sand	24					
Oils and lubricants separated from “dirty” sewage	24	+	+	+		
Non-hazardous waste: scrap	6	+	+	+	+	+
Risk of industrial accident: hardening oil	5	+	+	+		
Contact with extremely high-temperature objects	20	+	+	+	+	
Hot working conditions	30		+	+	+	
Contact with “oil mist”	16		+	+	+	
Skin and eye contact with chemicals	24	+	+	+	+	
Contact with sharp, protruding, and rough surfaces	16					
Contact with moving elements of machines and devices	24					
Material falling on the legs	9					
Slipping and falling on the same plane	9	+	+	+	+	
Overload of the musculoskeletal system	6					
Working in a standing position	10					
Noise exposure	10					
Stress	27		+	+	+	
Risk of industrial accident: fire, explosion	20		+	+	+	
IRR		171	351	326	264	30

Key technological parameters were identified via high integrated risk ratio values, higher than those described as the maxima. On this basis, the following are considered to be the key technological parameters:

- IRR = 351 for the austenitizing temperature, which may affect the presence of structures with a partial lack of hardening effects (IRR = 12 $\times$ 1), overheated, coarse structures (IRR = 9 $\times$ 1), temperature stresses (IRR = 75 $\times$ 1), electricity (IRR = 25 $\times$ 1), the water intake (IRR = 25 $\times$ 1), the presence of used quenching and hydraulic oils (IRR = 24 $\times$ 1), oils and lubricants separated from "dirty" sewage (IRR = 24 × 1), non-hazardous waste: scrap (IRR = 6 × 1), hardening oil and industrial accidents (IRR = 5 × 1), contact with extremely high-temperature objects (IRR = 20 × 1), hot working conditions (IRR = 30 × 1), contact with "oil mist" (IRR = 16 × 1), skin and eye contact with chemicals (IRR = 24 × 1), slipping and falling on the same plane (IRR = 9 × 1), stress (IRR = 27 × 1) and fire, explosions, and industrial accidents (IRR = 20 × 1);

- IRR = 326 for the heating time, which can have an impact on the presence of structures with a partial lack of hardening effects (IRR = 12 × 1), overheated, coarse structures (IRR = 9 × 1), temperature stresses (IRR = 75 × 1), the electricity intake (IRR = 25 × 1), the presence of used quenching and hydraulic oils (IRR = 24 × 1), oils and lubricants separated from "dirty" sewage (IRR = 24 × 1), non-hazardous waste: scrap (IRR = 6 × 1), hardening oil and industrial accidents (IRR = 5 × 1), contact with extremely high-temperature objects (IRR = 20 × 1), hot working conditions (IRR = 30 × 1), contact with "oil mist" (IRR = 16 × 1), skin and eye contact with chemicals (IRR = 24 × 1), slipping and falling on the same plane (IRR = 9 × 1), stress (IRR = 27 × 1) and fire, explosions and industrial accidents (IRR = 20 × 1).

The IRR can be treated not only as a reflection of the total risk associated with the occurrence of defects, environmental impacts, and the effects of occupational safety threats, but it also makes it possible to identify the technological parameters (in this case, the austenitizing temperature and heating time) that absolutely must be the subjects of operational supervision.

According to the methodology, the technological parameters of the process are adopted in the risk matrix only in the qualitative context. Thus, the calculations in the field of integrated risk have been simplified. At the same time, those parameters that ensure compliance with the quality requirements create environmental and occupational hazards have been indicated.

The key operational parameters for hardening operations, according to Figure 2, are as follows:

- Technological features described by high values of the unit risk ratio (URRq, URRe, URRs) and maximum values of priority numbers of occurrence, significance, and control or exposure (PRO, PRI, PRCI);
- Technological parameters are described by high values of the integrated risk ratio (IRR).

The applied methodology allowed for the identification of the key operational features (thermal stresses; surface oxidation; electricity intake; water intake; used quenching and hydraulic oils; oily wipes, sawdust and sand; oils and lubricants separated from "dirty" sewage; hardening oil; industrial accidents; high temperatures; working in a standing position; stress exposure; noise exposure; chemical substances; the moving elements of machines and devices; fire conditions) in the first stage and the key operational parameters (austenitizing temperature, heating time) in the second stage. For all of them, due to their key natures, the operational criteria should be defined and included in the operational monitoring.

The identification of the key technological features and parameters, which have been described for hardening operations, is only an exemplary way of determining the key operational parameters. However, the use of such an algorithm has allowed for the identification of controllable operational criteria and subjects them to operational monitoring. It is important for the monitoring to consider the verification of the compliance of the actual values of the operational parameters with the planned values of their operational criteria. Examples of operational criteria for the integrated range in heat treatment operations are summarized in Table 12.

The organization, by controlling the processes, determines the optimal and limit values for all the operational criteria, which are the criteria for releasing the processes. Thus, if, for example, the value of the operational criterion described as "temperature in the furnace working chamber" has been specified in the technological card as 1000 °C, then the achievement of such a temperature in the furnace chamber will mean that the requirement for this operational criterion has been met.

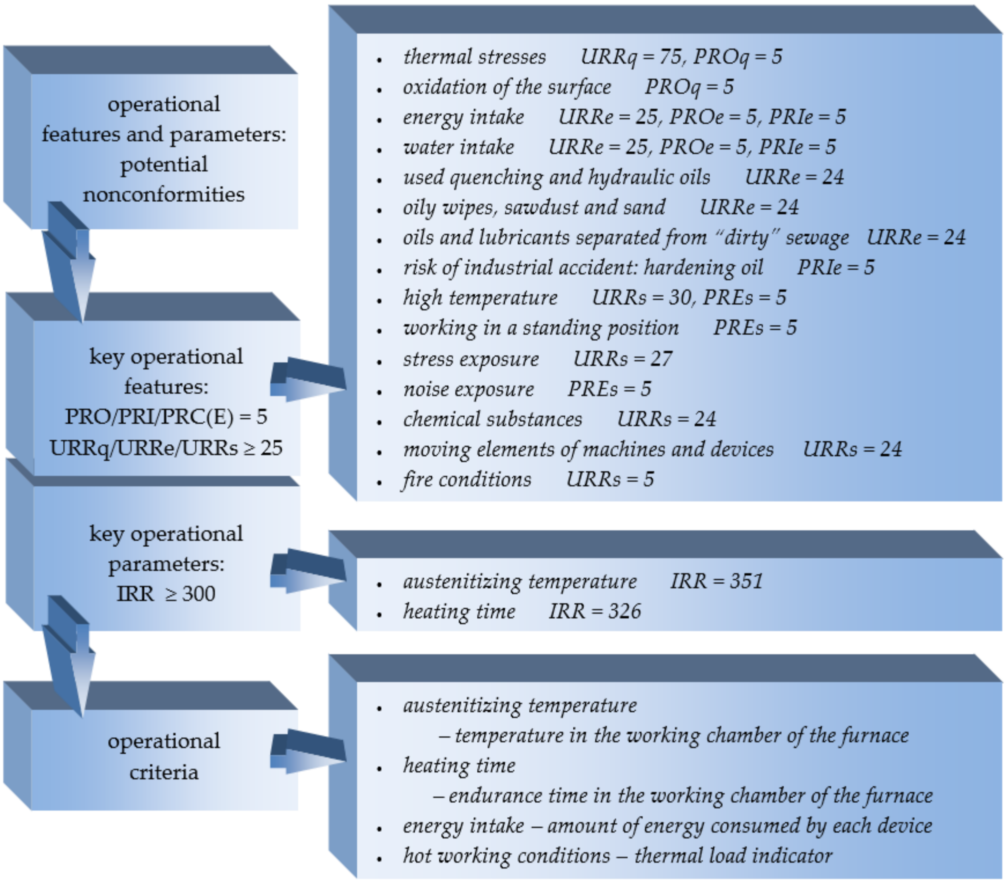

Figure 2. Scheme of identification of key operational parameters in the hardening operation.

Table 12. List of selected operational parameters and their criteria as well as possibilities of operational control.

Operational Parameters	Operational Criteria	Operational Control
Austenitization temperature	Temperature in the working chamber of the furnace	Ensuring a temperature in the working chamber of the furnace that allows for austenitization
Heating time during hardening	Endurance time in the working chamber of the furnace	Providing the time necessary for austenitization
Quenching oil temperature	The flow rate of the cooling bath through the hardening bath	Selection of the cooling speed of the quenching bath ensuring the optimum quenching temperature
Composition of the protective atmosphere	Flow rate of the protective atmosphere	Selection of the atmospheric flow velocity ensuring its optimal amount in the furnace working chamber
Parameters of alkaline washing bath	Temperature and concentration of alkaline solution	Ensuring parameters of the alkaline washing bath that guarantees the proper surface preparation of the workpiece before heat treatment
Different structure from the one planned	Process capability indicators	Ensuring the stability and planned capacity of the heat treatment operations
Energy intake	Amount of energy consumed by each device	Ongoing observation of energy consumption and comparison of it to the consumption pattern of a specific operation; identification of points of potential energy losses
Water intake	Amount of water used in each operation	Ongoing observation of water consumption and comparison of it to the consumption pattern of a specific operation; identification of points of potential water losses

Table 12. *Cont.*

Operational Parameters	Operational Criteria	Operational Control
Formation of industrial wastewater	Water consumption indicators for metal industry plants	Confirmation that the quantity will not be exceeded and the parameters enabling the introduction of industrial wastewater into sewage systems owned by another entity will be maintained
Hazardous waste	Amount of waste classified according to the waste catalog	Confirmation that the quantity of generated hazardous waste for which a permit has been issued will not be exceeded
Hot working conditions	Thermal load indicator	Ensuring the proper parameters of the supply of air (speed and temperature) of the ventilation, defining the optimal exposure time
Contact with moving elements of machines and devices	Number of accidents and accident situations at work due to contact with moving machine components	Taking actions to reduce human risk with dangerous factors by influencing the safe behavior of employees (e.g., providing training)

5. Conclusions

Operational activities, carried out in technological processes, often remain unintegrated, and the planned goals lie within the competences of various organizational units and are achieved via specific methods. This is due to different operational criteria. Therefore, methodologies reflecting the use of different models, methods, and tools in the integration of different operational goals are becoming increasingly important. In this area, research on modeling effective ways of integrating management at the operational level and on instruments for achieving the various sustainable operational goals of the organization is needed. The development of the operational control algorithm—dedicated to the sustainable realization of processes—is the answer to these needs. It confirms that, in technological processes, it is possible to ensure supervision that prevents the occurrence of non-compliance and minimizes its effects in the qualitative, environmental, and occupational safety contexts.

A consistent methodology for identifying, analyzing, assessing, and estimating the acceptability of the integrated risk in the technological process—taking into account the quality, environmental, and occupational safety criteria—is of crucial importance, making it possible to define defects, environmental aspects and occupational safety threats for which the individual risk is unacceptable and for which immediate actions should be taken for risk minimization. Moreover, the results—reflected by the specific values of the risk ratios—represent a starting point for identifying key operational parameters and indicating their operational criteria. This is an essential action from the perspective of the decision to include the parameters in operational monitoring, ensuring their compliance with the integrated requirements.

Both the method of integrated risk assessment and that of defining the key operational criteria determine the novelty of this research.

The application of the developed methodology for assessing the integrated risk of defects, environmental impacts and effects of occupational safety threats, and operational control to ensure the conditions of supervised risk during the implementation of hardening operations, supports the claim that the prepared model can be used in most technological processes implemented in organizations. The operational control model has been developed as a universal proposal for practitioners, aimed not only at ensuring the quality of products but also at minimizing the impacts of the associated processes on the surrounding environment and reducing occupational safety risks. Thus, it is a tool that supports systematic sustainable improvement in technological processes.

Funding: This research received no external funding. APC was funded by the Silesian University of Technology (Poland), grant no. 10/010/RGJ22/1086.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The author declares no conflict of interest.

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