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ANALYSIS AND EVALUATION OF WASTE MANAGEMENT LOGISTICS AND IMPROVEMENT PROPOSALS

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Abstract.
The growing volume and complexity of industrial waste streams present a significant challenge for enterprises, which must simultaneously comply with strict environmental regulations and maintain operational efficiency. Waste management logistics, a specialised branch of reverse logistics, plays a key role in organising processes related to the collection, segregation, storage, and transfer of waste for further processing or disposal. The research niche of this article lies in the limited operational assessment of how FMEA-based risk identification can support the integration of waste records, warehouse location management and digital tracking tools in industrial waste management logistics. The research problem addressed in this study concerns the insufficient integration and efficiency of waste management logistics systems in medium-sized manufacturing enterprises operating in the household chemicals industry. The research hypothesis assumes that improving waste logistics through the implementation of digital tools, standardisation, and process integration may significantly enhance the efficiency, transparency, and safety of waste management processes. The main objective of the article is to analyse and evaluate the functioning of the waste management logistics system in a selected enterprise and to develop practical improvement measures at the organisational, technological, and IT levels. The research employed the FMEA (Failure Mode and Effects Analysis) method, process documentation analysis, and direct observation. The results of the study support the research hypothesis, showing that the integration of digital tools, automation, and employee training may contribute to reducing operational risk, ensuring compliance with environmental regulations, and improving overall process efficiency. The findings highlight the strategic importance of waste logistics as a key component of sustainable development and corporate environmental responsibility in modern industrial enterprises.
Keywords:
waste management logistics; industrial waste; FMEA analysis; logistics process efficiency; waste management in industry

Introduction

Waste management logistics has become an indispensable element of comprehensive environmental management in industrial enterprises. In the era of advancing ecological transformation, regulatory pressure, and increasing social awareness, responsible handling of waste streams has ceased to be merely a legal obligation, it has become a key factor in gaining competitive advantage and an indicator of a company's operational maturity. Today, effective waste management requires not only compliance with national and EU regulations, but also a focus on cost optimisation, elimination of wastefulness, and increased transparency and oversight of waste-related processes.

This issue is particularly relevant in manufacturing enterprises, which generate significant volumes of various types of waste ranging from post-production residues and packaging waste to substances classified as hazardous. The scale and complexity of these waste streams require a precise logistical approach that encompasses the entire life cycle of waste within the organisation. This includes both physical activities such as segregation, internal transport, temporary storage, and transfer to external recipients and informational tasks, such as identification, labelling, recording, and reporting within integrated IT systems, such as the Warehouse Management System (WMS) and the Database on Products, Packaging and Waste Management (BDO).

Modern waste logistics increasingly relies on digital solutions, automation, and Industry 4.0 concepts, enabling real-time monitoring of environmental parameters, automatic identification of non-compliances, and the generation of decision-support analyses. At the same time, the importance of integrating waste logistics with other areas of enterprise operations such as production, quality management, maintenance, procurement, and planning is growing. A systems-based approach is key to reducing costs, enhancing safety, and implementing solutions aligned with the principles of the circular economy (CE).

The research problem concerns the insufficient integration, digitalisation, and operational efficiency of waste management logistics systems in industrial enterprises, which may result in non-compliance with environmental requirements and increased operational risks.

The research question was: How can FMEA-based assessment identify and prioritise critical risks in the waste management logistics process of a manufacturing enterprise, and what organisational, technological and IT improvements are required to increase process efficiency, traceability and safety?

The research hypothesis assumes that the implementation of digital solutions, automation, and standardisation of waste logistics processes may significantly improve the efficiency, safety, and environmental performance of the system. To verify this hypothesis, the study employed the Failure Mode and Effects Analysis

(FMEA) method used to identify critical points, combined with process observation and analysis of internal documentation.

Fundamentals of waste management logistics

According to the applicable Polish Act of 14 December 2012 on Waste, waste is defined as "any substance or object which the holder discards, intends to discard, or is required to discard due to applicable regulations or environmental safety considerations" (Dz. U. 2023 poz. 1587).

Waste management logistics represents an extension of the reverse logistics concept, encompassing processes that enable the reintegration of deactivated products or materials into the economic cycle. Its scope goes beyond the traditional understanding of waste management, which primarily focuses on the collection and treatment of waste. The core objective of waste logistics is to recover value from waste and to optimize material flows toward reuse. Its implementation is closely linked to ecological balance assessments and requires coherent systems for transport, collection, and disposal (Puzio 2018, pp. 112–113).

According to data from Statistics Poland (GUS), a total of 102.9 million tonnes of industrial waste were generated in Poland in 2024 (Figure 1), representing a 5.9% decrease compared to the previous year. The main sources included mining and quarrying (60.9 million tonnes, 60%), manufacturing (19.1 million tonnes, 18.6%), and construction (11.2 million tonnes, 10.9%). Most of the waste was either recovered (49.6%) or landfilled (44.5%) (Statistics Poland, 2025, pp. 154-155). Waste originating from industrial activities accounts for a significant share of the total waste generated in the country, which highlights the need for effective waste management at the enterprise level.

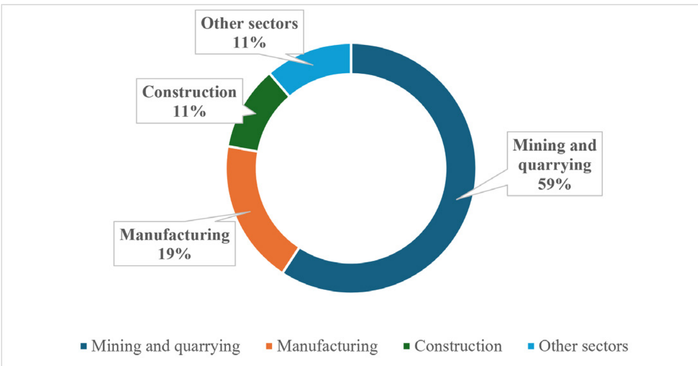

Figure 1. Structure of industrial waste in Poland in 2024
Source: own study (Statistics Poland, 2025)

As Brzeziński points out, the development of modern logistics systems requires a holistic approach, one that involves analysing the interrelationships between different system components and their impact on the overall functioning of logistics. The author emphasizes that "the integration of processes, technologies, and organisational structures forms the foundation for building efficient and safe logistics systems" (Brzeziński 2024, p. 140). In the context of industrial waste management logistics, such an approach allows for the design of waste systems as part of a broader, integrated enterprise management structure considering not only material flows but also safety, regulatory compliance, and cost optimisation.

Processes related to waste management logistics comprise a set of integrated activities aimed at planning, organising, supervising, and controlling the movement of waste streams from the point of generation to the stages of recovery, recycling, or disposal. These activities consider not only the physical flow of materials but also the flow of information and finances, which are essential components of a systems-based approach. A properly designed waste logistics system contributes to the optimisation of waste management within the enterprise, the reduction of operational costs, and the mitigation of pressure on the natural environment (Kłak et al. 2023, pp. 88–91).

The fundamental objectives of waste logistics can be divided into four key areas: economic, environmental, social, and organisational. From an economic perspective, waste logistics aims to reduce the costs associated with managing waste streams and to generate added value through the recovery and sale of secondary raw materials aligned with the concept of viewing waste as a potential commodity. From an environmental standpoint, the priority is to minimize the negative impact of waste processing and disposal on the surrounding environment. The social objective highlights the need to protect the health and quality of life of communities located in areas affected by waste-related activities. The final organisational objective focuses on the development of comprehensive, integrated waste management systems in accordance with the principles of sustainable development (Puzio 2018, p. 113).

According to Directive 2008/98/EC of the European Parliament and of the Council, waste management should be organized in accordance with the waste hierarchy (Figure 2), which includes: prevention, preparation for reuse, recycling, other recovery methods (e.g., energy recovery), and disposal (Dz. U. UE L 312 z 22.11.2008).

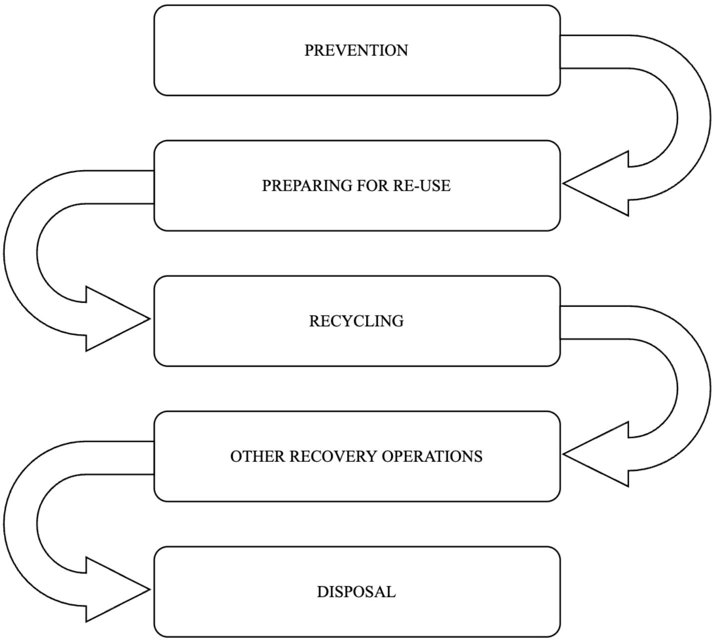

Figure 2. Diagram of the waste management hierarchy
Source: own study (Dz. U. UE L 312 z 22.11.2008)

Waste logistics is also a key component of the circular economy (CE), in which waste is viewed not merely as an environmental burden, but as a potential source of secondary raw materials. In the CE model, material flows do not end at the point of consumption but instead enter a new usage cycle enabled by recovery, processing, repair, and reuse (Zarębska 2017, pp. 287–291).

The effectiveness of a waste logistics system (Figure 3) depends on its integration with other departments within the enterprise, as well as on the organisation of supervision, communication, and employee competencies. In practice, this means the need to implement an integrated management model in which waste handling does not operate as a separate organisational unit, but rather as part of a harmonized process encompassing various levels and functions of the company (Puzio 2018, p. 113).

In waste management, logistics processes form a system of interconnected operations, including, among others, storage, material handling, preliminary material processing (such as segregation, shredding, or briquetting), as well as the recovery of secondary raw materials and energy. The direction of waste flows whether toward recycling or disposal depends on the adopted strategy of recovery as close to the source as possible and on the principles of minimizing resource losses. Effective execution of these tasks requires an integrated approach to managing information, storage space, and the organisation of both internal and external transport (Brzeziński 2006, pp. 84–89).

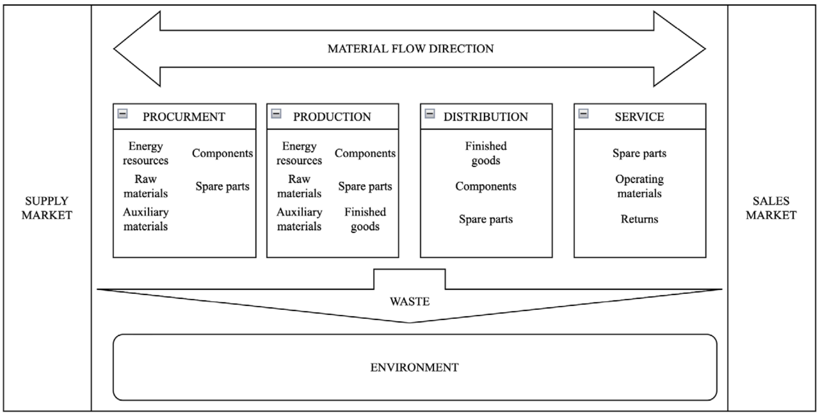

Figure 3. Flow diagram of industrial waste streams
Source: Czajkowski (2025, p. 27)

In the era of rapid digitisation of economic processes, waste management logistics is increasingly becoming a focal point of smart supply chain concepts. The integration of modern technologies such as the Internet of Things (IoT), Big Data analytics systems, and artificial intelligence not only enables real-time monitoring and automation of operations but also supports decision making related to recovery, sorting, and the transfer of waste to appropriate entities. In practice, this translates into the development of integrated and flexible waste management systems capable of responding quickly to disruptions while minimizing environmental and operational costs (Dymyt et al. 2024, pp. 185–187).

In the context of improving logistics systems related to industrial waste management, solutions based on the IoT concept are playing an increasingly important role. IoT is a key component of digital transformation in logistics and industry, enabling, among other things, remote monitoring of resources, integration of warehouse systems, and predictive maintenance of transport equipment. In particular, the application of IoT in logistics contributes to the improvement of processes such as warehouse management, inventory control, and real-time tracking of material flows (Górska and Daroń 2024, pp. 74–75).

In the context of waste management, IoT technologies can provide tangible support in automating waste tracking and registration, with applications in both internal warehouse flows and external reporting processes to systems such as the BDO. The ability to continuously identify waste containers, locate them within a

Warehouse Management System and integrate this data with the waste collection schedule represents a crucial element in streamlining waste logistics in manufacturing enterprises. Moreover, the implementation of IoT solutions enhances operational transparency and accuracy, which directly contributes to the overall efficiency of the system (Górska and Daroń 2024, p. 80).

The application of digital solutions in waste management aligns with the broader trend of supply chain evolution toward more resilient, transparent, and sustainable models. Modern supply chains should consider five key dimensions: instrumentation, integration, flexibility, servitization, and sustainability each of which can be directly applied to waste logistics, particularly in the context of automated decision making, waste flow monitoring, and minimizing environmental impact (Dymyt et al., 2024 pp. 185–187).

Waste logistics in the operational profile of company XYZ

The analysis of waste management logistics was carried out in a manufacturing company XYZ, located in the Masovian Voivodeship, operating in the household chemicals sector. The company is part of an international corporate group and serves both domestic and international markets. It specializes in the production of a wide range of cleaning products, such as laundry powders and liquids, stain removers, and dishwasher capsules.

The production facility is one of the key sites of the corporate group in Central and Eastern Europe, handling a significant share of order volumes for the European Union market. The plant operates in a continuous shift system, utilizing automated production lines and modern quality control systems.

The organisational structure of the company is functional in nature, meaning it is divided into departments responsible for specific functions such as production, logistics, quality, maintenance, research and development, controlling, and environmental protection. The plant is headed by a general manager who reports directly to the corporate board.

The waste management system at company XYZ is one of the key components of its integrated environmental and operational management framework. It has been developed to ensure compliance with both national and EU regulations, while also optimizing internal logistics processes. The core principles of the system are based on the identification, classification, segregation, temporary storage, and safe transfer of waste to external entities holding the appropriate permits.

Each type of waste generated as a result of production, warehousing, or support activities is assigned a specific code in accordance with the waste catalogue. To ensure consistency in handling procedures, the company has developed an internal waste register with assigned handling methods, which also includes requirements for packaging, labelling, and designated storage locations (tab. 1). Segregation takes place directly at the point of waste generation and is carried out by production operators, logistics personnel, and environmental staff, in accordance with established procedures and workstation instructions.

The system is organized around three levels of waste location: production units (point of generation), temporary staging areas within departments, and central collection points namely, the main staging area and the hazardous waste storage facility. Hazardous waste requires special handling, including separate labelling, dedicated documentation, and strict adherence to storage rules within designated zones adapted to the nature of specific hazards (flammable, toxic, oxidizing).

Table 1. Selected types of waste generated in company XYZ

No.	**Type of waste**	**Waste code**	**Waste handling procedure**
1	Mineral engine, gearbox and lubricating oils not containing halogenated compounds	13 02 05*	Transferred to hazardous waste storage
2	Paper and cardboard packaging	15 01 01	Segregated at source; Transferred to buffer zone
3	Plastic packaging	15 01 02	Segregated at source; Transferred to buffer zone
4	Wooden packaging	15 01 03	Segregated at source; Transferred to buffer zone
5	Metal packaging	15 01 04	Segregated at source; Transferred to buffer zone
6	Composite packaging	15 01 05	Segregated at source; Transferred to buffer zone
7	Packaging containing residues of hazardous substances	15 01 10*	Transferred to hazardous waste storage

Source: own study based on data from company XYZ

Figure 4 presents a mapped waste management process in the analysed company. Before any waste is transferred to external contractors, each load undergoes inspection, weighing, and registration. The waste must be properly secured and labelled with a tag containing the waste code, name, and source of origin. In the case of chemical substances, it must also be accompanied by a safety data sheet (SDS or PSDS). The waste tracking system is maintained using the national Waste and Packaging Product Management Database and each transfer is documented through outbound delivery notes (WZ) and entries in the waste transport register.

After all stages are completed, the waste is transferred to external recipients authorised for transport and disposal. The process concludes with the final disposal of the waste, confirmed by a destruction certificate and documentation entered into the BDO system.

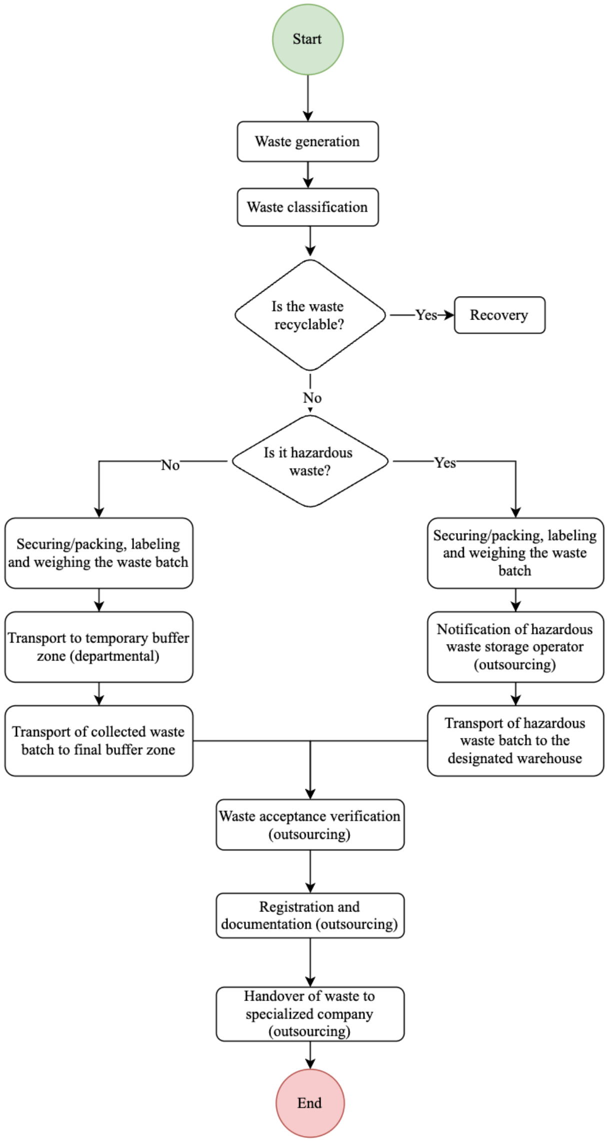

Figure 4. Process mapping of waste management in enterprise XYZ
Source: own study based on data from company XYZ

Analysis of the waste management logistics process in the selected company XYZ

Modern environmental management systems require enterprises not only to comply with legal regulations regarding waste management, but also to continuously improve internal processes, considering criteria such as efficiency, safety, and operational risk. One of the tools that enables systematic identification of hazards and assessment of their potential consequences is the Failure Mode and Effects Analysis method.

The main objective of this method is to identify potential failures in the process, analyse their causes and effects, and determine priorities for corrective actions. The analysis used three key evaluation indicators (Pac 2024, pp. 149–150):

O (Occurrence) – the likelihood of a given failure occurring (scale of 1–10),

S (Severity) – the significance of the failure's impact on the system (scale of 1–10),

D (Detection) – the ease of detecting the failure before its consequences occur (scale of 1–10).

The Risk Priority Number (RPN) is calculated using the following formula:

$$RPN = O \times S \times D \tag{1}$$

A high RPN value indicates the need for urgent corrective or improvement actions. In the present analysis, an RPN above 150 was considered to require immediate systemic or organisational intervention.

In this section, the FMEA method was applied to analyse the industrial waste management logistics system operating in company XYZ. The analysis covered the key stages of the process from the moment waste is generated during production activities, through its classification, labelling, internal transport, storage, and registration, to its transfer to external entities responsible for further processing or disposal.

The purpose of the analysis was to identify critical points in the process that could lead to major logistical disruptions, legal non-compliance, financial losses, or environmental hazards. The study was carried out in company XYZ, a manufacturer operating in the household chemicals industry.

The waste management logistics process in the company includes the following stages: waste generation, classification, labelling, segregation, temporary storage, internal transport, transfer to the staging area or hazardous waste warehouse, registration in the BDO system, and management of waste location and records.

In the first step, each stage of the process was analysed to identify potential non-conformities, their causes, and consequences. Subsequently, O, S, and D values were assigned based on process observations, employee interviews, and internal documentation (procedures, environmental reports, and registration records).

In the next step, RPN values were calculated to determine the priorities for improvement actions. The analysis covered 14 critical points in the process. Table 2 presents the analysis of potential failures in the waste management logistics system, in accordance with the FMEA methodology.

The table includes 14 distinct hazard scenarios, each accompanied by a technical commentary highlighting the significance of the identified issue in terms of both environmental regulatory compliance and its impact on operational continuity and internal safety. For example, incorrect waste identification not only poses a risk of administrative penalties but may also result in improper storage of hazardous substances, threatening employee health and infrastructure integrity. Similarly, errors in electronic documentation (e.g., within the BDO system) expose the company to financial liability and potential loss of credibility with external partners.

For each case, preventive and corrective actions were also described, showing how specific measures can effectively reduce the level of risk both through technical solutions (e.g., environmental monitoring sensors, automated labelling systems) and organisational actions (training standardisation of procedures, implementation of digital control forms). All of this allows the FMEA analysis to be treated not only as a diagnostic tool, but also as a foundation for planning strategic development initiatives within waste logistics.

Table 2. Results of the FMEA analysis

No.	Process stage	Potential non-conformity	Effect	Cause	O	S	D	RPN
1	Waste generation	Waste generated due to suboptimal production process settings	Increased amount of post-production waste, higher production costs, and greater load on the waste management system	Lack of regular process parameter analysis and insufficient quality monitoring at the production stage	3	8	4	96
2	Waste classification	Incorrect assignment of waste code from the waste catalogue	Risk of legal violations and improper waste handling	Lack of knowledge of current regulations and insufficient employee training	3	9	7	189
3	Labelling	Missing waste identification label	Risk of waste being rejected, delays, and risk of errors	Supply interruption of labels, printer failure, or employee error	4	5	3	60
4	Labelling	Incorrect label	Improper further processing, delays	Poor print quality	4	5	3	60

5	Segregation	Lack of segregation	Violation of environmental regulations	Haste or negligence	2	6	5	60
6	Temporary storage	Improper storage method	Safety hazard	Lack of knowledge of current regulations and insufficient training on available procedures for employees	4	9	4	144
7	Temporary storage	Lack of up-to-date storage security	Risk of contamination	Failure to inspect sensors and verify markings	1	10	6	60
8	Internal transport	Improper securing of waste batch	Damage to waste, risk of negative impact on the environment and people	Operator errors	4	7	3	84
9	Internal transport	Missing label during transport	Batch rejection	Negligence in labelling	3	8	5	120
10	Transfer to accumulation area	Lack of confirmation of receipt	Lack of correct logistics path	Employee not trained	3	6	5	90
11	Hazardous waste storage	Storage inconsistent with hazard classification	Explosion / fire	Employee error, lack of supporting system	4	10	6	240
12	BDO documentation	Incomplete records	Lack of audit compliance	Employee error, lack of supporting systems	6	8	5	240
13	BDO documentation	Error in entering data into BDO	Administrative penalties	Employee error, lack of supporting systems	5	8	5	200

14	Registration and waste location management	Lack of integration between waste records and WMS	Difficulty in identifying storage location, delays, and risk of errors in records	Lack of proper interface between IT systems	10	8	10	800

Source: own study based on data from company XYZ

The FMEA analysis made it possible to identify key risk areas in waste logistics, with the highest RPN values (above 200) observed for such issues as the lack of integration between waste records and the WMS (RPN = 800), incomplete documentation in the BDO system (RPN = 240), and improper storage in the hazardous waste warehouse (RPN = 240). The identified non-conformities may lead to serious legal, environmental, and operational consequences.

The greatest risks are associated with the lack of data integration and automation. The issue of registering waste without linking it to its physical location in the WMS system generates a high risk of errors and significantly complicates the execution of audits.

The second major area of risk involves human errors, resulting from insufficient training, inadequate supervision, and weak system support. Issues such as incorrect waste classification or mislabelling can lead to serious legal violations and environmental consequences.

Particular attention should also be paid to irregularities in the storage of hazardous waste – a potential mismatch with hazard classifications may pose a serious threat to the health and safety of employees and the surrounding environment.

Based on the conducted FMEA analysis, several non-conformities were identified that significantly affect the effectiveness and safety of the waste management logistics system in the company. Accordingly, a set of improvement recommendations was developed, aimed at reducing risk, enhancing regulatory compliance, and increasing operational efficiency. Among the proposed improvements are the following:

Integration of waste records with the WMS – the highest RPN value (800) was assigned to the non-conformity related to the lack of integration between waste registration and the warehouse management system. The current practice, based on separate Excel spreadsheets and manual data entry into the BDO system, leads to a risk of errors, record discrepancies, and operational delays. It is recommended to implement an interface enabling automatic data synchronisation between systems. The goal should be to ensure that every waste item generated during the process is promptly registered in the warehouse system and assigned to a specific physical location. The system should also allow tracking of location history, expiration dates, and the status of accumulated waste batches.

Automatic assignment of storage locations based on waste code – errors in waste storage, especially hazardous waste, often result from manual location selection by employees, creating a risk of improper storage. It is recommended to implement rules for automatically assigning warehouse locations depending on the waste code and its hazard classification. The system should include a functionality that blocks the acceptance of waste into a location incompatible with its ADR classification. Implementing this feature will reduce the risk of fire, leakage, or explosion.

Implementation of QR codes and mobile terminals – deficiencies in labelling and errors in entering data into the BDO system share a common root cause: the use of paper labels and manual data input. It is recommended to implement a QR code system that automatically generates labels based on waste batch parameters (waste code, weight, origin, date). Employees should be equipped with mobile terminals enabling label scanning and immediate waste registration in the system, which will reduce operation time and minimize the risk of human error.

Periodic training for operational staff and shift leaders – errors in classification, documentation, and storage are often the result of insufficient staff training. Although current regulations require the implementation of environmental procedures, their practical application frequently falls short of the expected standard. It is recommended to introduce mandatory, periodic in-house training on waste management, up-to-date legal regulations (including the Waste Act and the Waste Catalogue Regulation), and the use of registration systems. Training sessions should be supplemented with competency tests and instructional materials in digital form (e-learning).

Standardisation of labels and emergency printing system – a printer failure or lack of labels can halt the waste registration process or lead to incorrect identification. Missing labels disqualify a batch from further processing and may result in its rejection. It is recommended to implement standardized waste label templates and ensure access to backup printers (e.g., mobile printers). Additionally, the system should include an automatic reminder function prompting labelling before internal transport.

Conclusion

The analysis of waste management logistics in a household chemicals industry company revealed that, despite compliance with legal regulations and the implementation of basic registration and technical procedures, the system does not operate in a fully optimized manner. Shortcomings were identified in the areas of IT integration, waste traceability, and the organisation of storage and transport processes. The results of the FMEA assessment clearly pointed to areas particularly vulnerable to risk such as incorrect waste classification, lack of labelling, and insufficient automation of waste location registration.

Based on the results obtained, a few organisational and technological improvements were proposed. These include the implementation of integrated IT systems (combining BDO and WMS modules), the extension of labelling to include QR codes, the introduction of automatic waste location assignment in the warehouse, and increased frequency of staff training. These recommendations aim not only to improve operational efficiency, but also to enhance transparency, safety, and compliance with audit and environmental requirements.

The identified issues and proposed solutions form a foundation for further development of the company's waste logistics system and may also serve as a reference point for other industrial organisations seeking ways to improve their waste-related processes. Ultimately, effective waste management logistics becomes not only a legal necessity but also a strategic component of operational and environmental management in a modern enterprise.

The obtained results support the validity of the research hypothesis. The application of digital tools and process integration in waste logistics may significantly improve the operational efficiency, traceability, and safety of the system, supporting the overall environmental strategy of the enterprise. The results of this study also have a broader, international dimension and may be applicable beyond the analysed case of a Polish manufacturing enterprise.

The identified challenges related to the integration of IT systems, waste traceability, process standardisation, and the use of digital technologies are common across many industrial sectors globally.

Solutions such as the implementation of integrated WMS systems, the use of QR codes, automation, and the application of Industry 4.0 concepts can be successfully transferred to enterprises operating in other countries and industries. These tools may support the development of more transparent, efficient, and sustainable waste management systems in line with the principles of the circular economy.

At the same time, certain elements of the analysed system are specific to the Polish regulatory environment, particularly the use of the BDO system, which is a national database for waste registration and reporting. Therefore, while the technological and organisational solutions are widely transferable, their implementation may require adaptation to local legal frameworks and reporting systems in other countries.

This study is based on a single case study of one enterprise. Therefore, broader validation of the results would require comparative research across multiple companies and industries.

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