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Managing Warehouse Risks for 3PL Providers: A Novel Approach Based on FMECA-DEA

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Abstract: Warehousing serves as a critical component in the logistics chain, functioning as an intersection for inbound and outbound flows of goods before distribution to end customers. Given the complexity of warehousing operations, which involve numerous processes, activities, and workforce engagement, significant risks are inherently present. Consequently, a comprehensive risk analysis is imperative for effective risk management. Such analysis informs risk evaluation and facilitates the determination of appropriate mitigation strategies, with the goal of prioritising risks based on their potential impact. The objective of this study is to present a novel approach for risk assessment in warehouses operated by third-party logistics (3PL) companies, employing a combination of Failure Modes, Effects, and Criticality Analysis (FMECA) and Data Envelopment Analysis (DEA). The proposed framework aims to optimise risk prioritisation and to support the implementation of targeted preventive and corrective measures, thereby enhancing workplace safety and operational efficiency. This approach has been applied to a case study of a 3PL provider operating in the Serbian market, where 14 specific risks were identified and assessed. The most critical risks included falls from height, items falling from shelves during handling, forklift operations, and machinery-related risks involving packaging machines, electrical equipment, industrial cleaners, heaters, and forklift battery charging—particularly with regard to potential explosion hazards due to hydrogen gas release and acid spills. Based on the risk assessment, a series of preventive and corrective measures were formulated to mitigate the identified risks, thereby reducing the likelihood of occupational incidents, injuries, and fatalities. The integration of FMECA and DEA has been demonstrated as an effective methodology for systematically evaluating risks in warehouse operations, offering a robust basis for improving safety measures in logistics environments.

Keywords: Logistics; Risks; Warehouse; 3PL (Third-Party Logistics); Failure Modes, Effects, and Criticality Analysis (FMECA); Data Envelopment Analysis (DEA)

1. Introduction

To address the spatial and temporal mismatches in production, exchange, and consumption, product inventories are formed, which must be protected, stored, and, when necessary, transported and shipped. Thus, a dedicated space must be provided for this purpose. This space is known as a warehouse. A warehouse serves as a facility for storing goods, either in bulk or packaged, with the intention that, after a certain period, the goods will be integrated into further transport, production, distribution, or consumption. The warehousing system temporarily halts the movement of goods to ensure synchronization of the processes that precede and follow storage. Every warehouse should operate as an efficient, economical, and safe system. Ensuring the safety of warehousing processes is a complex challenge, as the storage space itself is a site where various types of accidents can occur.

Warehouses, as locations for storage, handling, transport operations, and goods manipulation, are places where various accidents can occur. The consequences of such accidents can include employee injuries, material damage, and environmental harm. Therefore, special attention must be paid to the safety of these processes by studying possible causes of accidents and conducting a detailed analysis of the processes themselves and the psychology of the workers involved. According to data from the International Labour Organization (2024), about 30% of all workplace accidents are related to storage incidents. Considering that over 250 million workplace accidents occur annually and 160 million people fall victim to work-related illnesses, it is evident that the safety of handling and storage processes is compromised by significant risk (International Labour Organization, 2024). Simply put, among all workplace injuries, those occurring during the execution of various goods handling processes are the most frequent.

The primary objective of this paper is to assess the safety conditions in warehouses and identify potential risks that could compromise safety. In order to achieve this goal, a model based on FMECA and DEA methods was proposed. The proposed model was then tested on data from a 3PL company operating in the Serbian market. Additionally, the paper emphasizes the importance of implementing risk management methods, specifically risk assessment, which are increasingly being adopted to achieve a higher level of workplace safety.

The methodology of this paper is structured as follows: after the introduction, in the second section, a problem description as well as a literature review are presented. The methodology of the paper is described in detail in the third section. The case study description, as well as the results, are presented in the fourth section. In the final, fifth section, concluding remarks, limitations, and future research directions are provided.

2. Problem Description and Literature Review

As previously mentioned, a warehouse is a space where the processes of handling, or manipulating goods, as well as storing, sorting, and picking, occur. Activities within a warehouse can pose various hazards. The fatal injury rate for the warehousing industry is higher than the national average for all industries. This statistic arises due to warehouse activities, involving the use of lifting equipment and general handling of goods, such as cranes, forklifts, and trucks, which are extensively used not only in warehouses but are also integral to various public infrastructures (Prameswara & Djunaidi, 2018).

For this reason, a risk assessment was necessary. It can be said that risk assessment is the most crucial phase in the field of occupational safety and health, and it will be discussed in more detail in the following sections of this paper. A good risk assessment can improve a company's competitiveness and proper risk management to achieve company objectives (Prameswara & Djunaidi, 2018). The term warehouse process safety encompasses the following areas: occupational safety, workplace safety, and fire safety.

Occupational safety encompasses activities and procedures implemented to protect personnel from injuries. This is a highly significant area of safety, considering that the presence of handling and transportation equipment, as well as the general handling of goods, are potential sources of injuries. Additionally, the aspect of handling hazardous goods must not be overlooked.

Workplace safety involves addressing issues related to protecting the atmosphere from various pollutants or noise, which can jeopardize the physical and mental health of employees. Although these issues are less prevalent, they still represent a significant aspect of protecting warehouse employees. These issues primarily result from the presence of different handling and transportation equipment that emit pollutants or goods that generate dust or otherwise contaminate the atmosphere, affecting both the workplace environment and the broader surroundings.

Fire safety consists of activities aimed at protecting personnel and property from fires and explosions. This is the most critical aspect of safety in warehouses designed to store toxic and highly flammable goods.

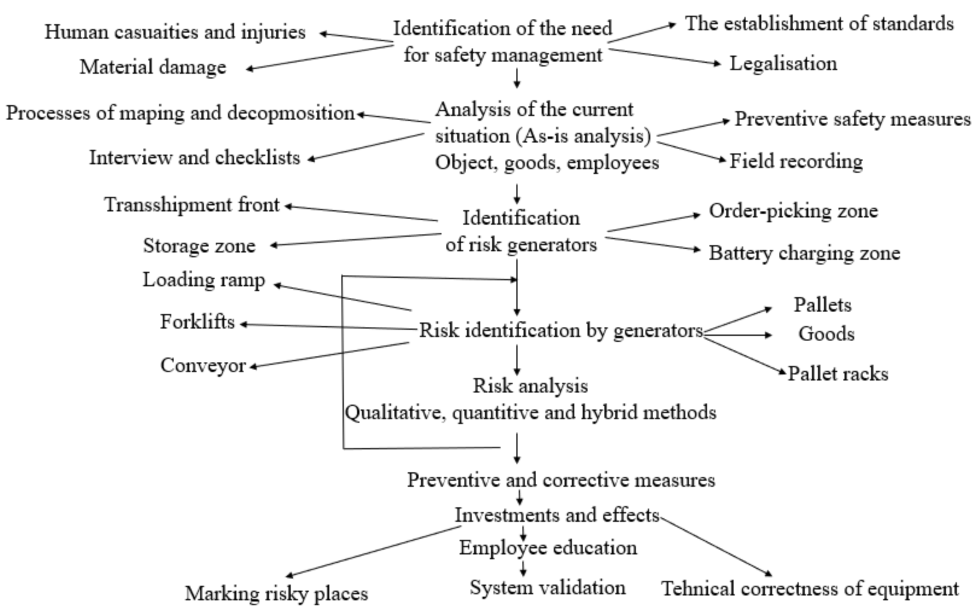

Figure 1. Framework for improving warehouse safety (Đurđević et al., 2022)

It can be concluded that safety is a result of, on the one hand, the characteristics of the stored goods; on the other hand, the applied technology and methods of executing warehouse processes. The stored goods can themselves pose a danger due to their physical and chemical properties. Therefore, warehouse personnel must study the characteristics of the goods being stored and, by using protective measures, ensure both their own safety and the safety of the goods in the warehouse. Warehouse safety is recognized as highly important both in practice and in literature. For instance, Đurđević et al. (2022) proposed a framework for improving warehouse safety. The proposed framework includes several steps, as shown in Figure 1.

Similarly, Hofstra et al. (2018) examined how warehouse safety can be assessed and facilitated by Logistics Service Providers (LSPs). On the other hand, Cantini et al. (2020) implemented a spaghetti chart to analyze the layout as well as the movement of the forklifts in order to reduce the risk of collision between forklifts and improve the operators' safety. Halawa et al. (2020) analyzed how real-time location systems (RTLS) can enhance warehouse safety and operational efficiency. The authors proposed a three-phase framework for RTLS technology introduction in the warehouse. Jang & Chen (2013) conducted a field study to determine the hazards and risks associated with warehouse workers. A fuzzy Analytic Hierarchy Process (AHP) was applied by Cebi & Ilbahar (2018) to assess the warehouse risks. Inam et al. (2018) assessed the risks associated with human-robot collaboration in an automated warehouse using Hazard Operability (HAZOP). Based on the conducted research, the authors proposed safety recommendations for reducing the risks. A combination of Failure Mode and Effects Analysis (FMEA) and DEA methods was used by Andrejić et al. (2020) to manage risks that are present in logistics. The proposed approach used the DEA method for improving the Risk Priority Number (RPN) calculation. Pajić & Andrejić (2023) implemented the Fine-Kinney method for the evaluation of occupational health and safety risks in internal transport. Mzougui et al. (2020) assessed the supply chain risks in the automotive industry by applying a modified Multi-Criteria Decision-Making (MCDM)-based FMECA. The proposed model includes implementing the FMECA, AHP, and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. In order to assess the risks associated with the distribution process, Pajić et al. (2023) implemented an FMEA- Quality Function Deployment (QFD) method. Risks associated with the use of drones in warehouse were examined and assessed by Tubis et al. (2021). AHP method was applied by Ren (2012) for assessing the fire risks in logistics warehouse. Andrejić & Kilibarda (2018) examined the risks of freight forwarders' activities when organizing the international commodity flows using FMEA method. Md Hanafiah et al. (2022) implemented AHP method to evaluate 13 risk factors that affect warehouse productivity.

3. Methodology

The proposed methodology consists of three phases. In the first phase, it is necessary to identify the area for which risks need to be reduced and/or eliminated. Following that, in the second phase, a list of all risks present in that area must be created, and their evaluation should be performed using the FMECA method. The results of the FMECA evaluation are then applied in the third phase of the model, using the DEA method to assess and determine which risks are prioritized and have the highest RPN number (Figure 2).

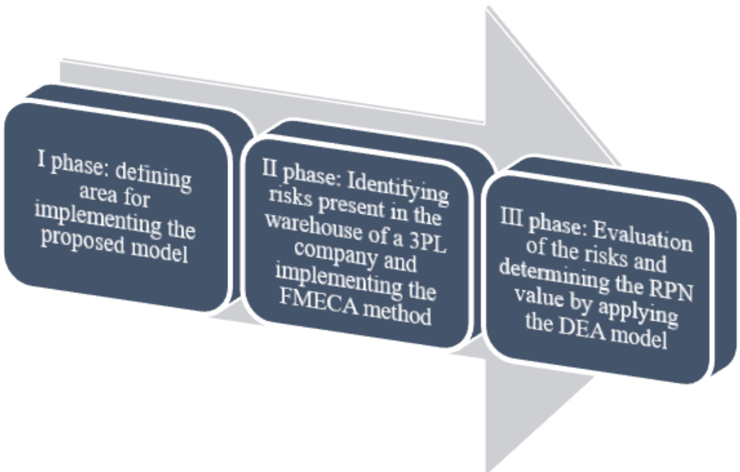

Figure 2. Methodology of the paper

3.1 FMECA Method

The FMECA method is a preventive approach used to systematize and schematically present the causes, effects, and possible measures for addressing identified critical points (Di Nardo et al., 2022). This method focuses on analyzing the impacts and consequences of failures, particularly during the risk identification phase and in defining measures to eliminate their causes and, consequently, their effects. Within the FMECA method, risk fulfillment is viewed as the occurrence of a failure. Therefore, by identifying potential failures, potential workplace safety risks are also determined. FMECA serves as a tool for identifying risks to workplace safety and health, uncovering their causes, assessing hazards, and proposing measures to reduce their occurrence. The analysis parameters are numerically evaluated; thus, the final risk assessment in the workplace and working environment is also expressed numerically. In order to evaluate the risks, three risk components should be determined: the probability of failure occurrence (R1), the severity of the failure (R2), and the probability of failure detection (R3) (Di Nardo et al., 2022). The value of these components is presented in Table 1. The final RPN value is determined using Eq. (1).

$$RPN = R1 \times R2 \times R3 \tag{1}$$

Table 1. Values of the components

Value	R1 (Occurrence)	R2 (Severity)	R3 (Detection)
1	It does not occur	None	It can certainly be detected
2	Negligible probability	Negligible	Very highly
3	Very low probability	Very low	Highly
4	Low probability	Low	Relatively highly
5	Less than medium probability	Significant	Medium
6	Medium probability	Very significant	Relatively small
7	More than medium probability	Severe	Small
8	High probability	High	Very small
9	Very high probability	Very high	Negligible
10	Certain occurrence	Catastrophic	Hardly detectable

After the evaluation is completed, based on the RPN value, risk can be classified into one of the following categories (Table 2).

Table 2. Risk categories

Category	RPN Value	Classification
1	RPN ≤ 10	Acceptable risk
2	10 ≤ RPN ≤ 100	Acceptable risk (Monitoring is advised)
3	100 ≤ RPN ≤ 200	Increased risk - conditionally acceptable risk
4	200 ≤ RPN ≤ 400	Unacceptable risk
5	RPN > 400	Unacceptable risk (Risk is unmanageable)

3.2 DEA Method

The DEA method was used in this paper to determine the RPN value based on which risk priority can be determined. For this purpose, the Charnes-Cooper-Rhodes (CCR) input-oriented model was used, which can be presented as follows (Chen et al., 2024; Ji & Lee, 2010; Zhang et al., 2024):

$$\max \sum_{r=1}^{s} u_r y_{rj} \tag{2}$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \ \ \forall j \tag{3}$$

$$\sum_{i=1}^{m} v_i x_{ij} = 1 \tag{4}$$

$$u_r, v_i \geq 0, \forall \mathrm{r}, \forall \mathrm{i} \tag{5}$$

where, j corresponds to the number of Decision-Making Units (DMUs) ($j=1, 2, \ldots, n$), m represents the number of inputs ($x_{ij} = 1, 2, \ldots, m$) while s represents the number of outputs ($y_{rj} = 1, 2, \ldots, s$). y_{rj} corresponds to the amount of the r^{th} output from DMU_j; u_r represents the weight given to the r^{th} output; x_{ij} represents the amount of the i^{th}

input used by DMU_j; while v_i represents the weight assigned to the i^{th} input.

4. Case Study – Risk Analysis in the Warehouse of 3PL Provider Company X

The central logistics center of Company X is situated in the heart of the industrial zone of Belgrade. It employs over 1,000 people and covers approximately 55,000 square meters of warehouse space. Company X handles more than 6,000 deliveries daily. By continuously monitoring warehouse occupancy, the company effectively manages available capacities used in the logistics segment. In addition to distribution, the storage sector within logistics is responsible for receiving, storing, and preparing goods for delivery according to customer requirements. Efficient management and optimal utilization of all warehouse resources are supported by a computerized warehouse management system. This advanced system enables the company to store over 10,000 products while applying best warehousing practices and achieving a delivery accuracy rate exceeding 99.5%.

Employee safety is of paramount importance. Therefore, Company X places a strong emphasis on maintaining safe working conditions and complies with all relevant safety laws. It is essential that all employees adhere to and enforce workplace safety regulations and company policies to ensure the highest level of safety for everyone. All employees are covered by an accident insurance policy, which provides protection for both work-related and non-work-related accidents throughout the year. The Safety Sector oversees the health and safety of employees and third parties within Company X's business premises. By decision of the director, a 10-member team has been established to manage these responsibilities, coordinated by the safety manager, and composed of employees from various sectors across all operational locations. Company X records and reports all hazardous situations, minor and severe injuries, as well as other health risks. All reported incidents are analyzed annually.

The facilities are equipped with state-of-the-art warehouse equipment and technology, including a Pick by Voice system. Upgrading the existing system significantly enhances worker safety standards and improves overall productivity and storage accuracy. The warehouse uses various types of equipment and internal transportation means, such as forklifts, pallet trucks, and conveyor systems. Goods are stored in block storage systems and high-bay racks, depending on the specific type of goods being stored. Despite precautionary measures, potential risks to worker safety and health may still arise in certain situations. With this in mind, potential causes of accidents in the warehouse have been identified and evaluated using a linguistic scale as the first step in the risk assessment process (Table 3).

Table 3. Possible risks in the warehouse

Number	Risk	R1	R2	R3
1	Fall from height	Low probability	Catastrophic	Negligible
2	Regular transportation of boxes to the loading dock	High probability	High	It can certainly be detected
3	Slips, trips, and falls	Certain occurrence	Low	Relatively small
4	Items falling from shelves during handling	Medium probability	Very high	Medium
5	Forklift operations	Low probability	Catastrophic	Relatively small
6	Packaging machines	Medium probability	Catastrophic	Medium
7	Electrical equipment, industrial cleaners, heaters	Medium probability	Catastrophic	Relatively small
8	Fire caused by the storage of highly flammable materials	Negligible probability	Catastrophic	Medium
9	Faulty electrical installations			
10	Battery charging			
11	Hazardous substances and exhaust gases from vehicles performing loading and unloading	Negligible probability	Significant	Very highly
12	Bleaching and cleaning agents	High probability	Significant	Very highly
13	Forklift battery charging – potential explosion due to hydrogen gas release, acid spills	Low probability	Very high	Medium
14	Lighting	Certain occurrence	Severe	It can certainly be detected

Based on the assessment presented in Table 3, a linguistic assessment was converted into numbers in order to determine the RPN value using Table 1. In this way, Table 4 has been created.

Following this evaluation and the application of the FMECA method, the model progressed to the second phase, which involved the application of the DEA method. The values from Table 4 were used as input parameters for the DEA method: R1 as input 1 (I1), R2 as input 2 (I2), and R3 as input 3 (I3), with each risk being treated as a distinct DMU. Conversely, all risks were assigned a value of 1 for the output parameter 1 (O1). Consequently, the

DEA model comprises 3 inputs and 1 output (Table 5).

Table 4. Risks evaluation

Number	Risk	R1	R2	R3
1	Fall from height	4	10	9
2	Regular transportation of boxes to the loading dock	8	8	1
3	Slips, trips, and falls	10	4	6
4	Items falling from shelves during handling	6	9	5
5	Forklift operations	4	10	8
6	Packaging machines	6	10	5
7	Electrical equipment, industrial cleaners, heaters	6	10	8
8	Fire caused by the storage of highly flammable materials			
9	Faulty electrical installations	2	10	5
10	Battery charging			
11	Hazardous substances and exhaust gases from vehicles performing loading and unloading	2	5	2
12	Bleaching and cleaning agents	8	5	2
13	Forklift battery charging – potential explosion due to hydrogen gas release, acid spills	6	9	5
14	Lighting	10	7	1

Table 5. Input data for the DEA model

DMU	I1	I2	I3	O1
DMU1	4	10	9	1
DMU2	8	8	1	1
DMU3	10	4	6	1
DMU4	6	9	5	1
DMU5	4	10	8	1
DMU6	6	10	5	1
DMU7	6	10	8	1
DMU8	2	10	5	1
DMU9	2	10	5	1
DMU10	2	10	5	1
DMU11	2	5	2	1
DMU12	8	5	2	1
DMU13	6	9	5	1
DMU14	10	7	1	1

Table 6. DEA results

DMU Name	Objective Value	Efficient
DMU1	**0.5**	
DMU2	1	Yes
DMU3	1	Yes
DMU4	**0.538461538**	
DMU5	**0.5**	
DMU6	**0.488888889**	
DMU7	**0.488372093**	
DMU8	0.999996	
DMU9	0.666666667	
DMU10	0.617647059	
DMU11	1	Yes
DMU12	0.999998	
DMU13	**0.538461538**	
DMU14	1	Yes

Based on the aforementioned points, the DEA CCR input-oriented model was applied to obtain the results. Unlike the traditional RPN number, in this model, the efficiency scores are calculated using the FMECA-DEA approach. In this approach, higher efficiency scores indicate lower RPN values, while lower efficiency scores correspond to higher RPN values, meaning these risks should be prioritized when defining preventive measures (Andrejić et al., 2020). In this study, a threshold of 0.6 was set, meaning that all DMU units (risks) with a value less than 0.6 were considered critical and in need of preventive-corrective measures. The results of the application showed that six risks were prioritized (fall from height, items falling from shelves during handling, forklift operations, packaging machines, electrical equipment, industrial cleaners, heaters, and forklift battery charging – potential explosion due to hydrogen gas release, acid spills) and should be addressed first (Table 6).

Based on the obtained results, preventive and corrective measures were proposed for each risk to reduce and/or eliminate them. For the first risk (fall from height), the maintenance worker should inspect the guardrail to ensure it is in proper condition and securely fastened before each use. Additionally, "fragile roof" signs should be placed at roof access points. If there is a need to lift workers, the use of safety harnesses and helmets is mandatory. For the second risk (items falling from shelves during handling), the following preventive and corrective measures can be defined: placing signs on shelves indicating maximum load/configuration and securing goods to prevent them from falling. Regarding the risk of forklift operations, it is necessary to check the standards of order and cleanliness and the condition of the floors monthly, and keep records of these inspections. Pedestrian entrances should be separated with protective wire fencing, and it should be strictly required that only trained operators drive forklifts, with disciplinary measures taken against those who violate this rule. Additionally, everyone working near moving vehicles should undergo training and wear highly visible clothing. The risk associated with packaging machines can cause serious consequences, so it is essential to define proper preventive measures, such as ensuring the area around the machine is free of obstacles and marked with fluorescent paint. In addition, weekly checks of the guards and the condition of the machines are required. Preventive and corrective measures for the next risk (electrical equipment, industrial cleaners, heaters) can include more frequent (semi-annual) inspections and testing of equipment, as well as instructing workers to report malfunctions immediately. One of the risks that can pose serious health and safety threats to warehouse workers is forklift battery charging – potential explosion due to hydrogen gas release, acid spills. To reduce and/or eliminate this risk, the following measures can be implemented: the warehouse supervisor should monitor the situation and ensure that protective equipment is used without exception, check the battery condition before charging, check the battery condition after charging and before installing it in the forklift, etc.

5. Conclusions

Creating a safe and productive warehouse environment begins with developing and gradually instilling a safety culture, which involves increasing awareness about the importance of workplace safety and health protection. This safety culture must be continually reinforced at all levels, with managers, especially supervisors and company owners, playing a critical role as primary advocates, including for warehouse systems. Establishing a safe working environment starts with a comprehensive safety plan that covers all areas of the warehouse and applies to all employees. Owners and managers should anticipate investing time and resources into safety measures and willingly integrate these costs into the overall budget. Employers must keep in mind that safe employees are not only more productive but are also more likely to remain loyal to the company.

In this context, risk assessment is intrinsically linked to the concept of safety. The purpose of risk assessment is to help companies understand all aspects of risks that could lead to potential undesirable events. Various risk assessment methods are applied to protect employees from injuries and other health hazards during work, making their effective implementation a crucial aspect of warehouse operations.

This paper implemented a combination of FMECA and DEA methods, which are described and explained in detail. Through a specific example, a risk assessment was conducted for workers exposed to risks in Company X’s warehouse. The results showed that six risks should be prioritized when defining preventive-corrective measures. These risks are the following: fall from height, items falling from shelves during handling, forklift operations, packaging machines, electrical equipment, industrial cleaners, heaters, and forklift battery charging – potential explosion due to hydrogen gas release, acid spills. Based on these results, the level of safety can be determined, and both corrective and preventive measures were defined to enhance overall warehouse safety. The main contribution of the paper is reflected in the fact that the proposed model is unique and the combination of the methods used in this paper has not yet been used. Also, by applying the proposed model, decision-makers can easily identify the risks that are present in their company and therefore create a safer working environment for their employees.

The limitation of this paper is reflected in the fact that only 14 risks were taken into account, and they are associated only with the warehouse. Hence, in the future papers, risks associated with transport, distribution, procurement, and other segments of logistics should be taken into account. Regarding future research directions, one of the main areas is certainly the application of the proposed model to larger-scale examples, as well as its application to other segments of logistics. Additionally, combining the proposed model with other methods to create a hybrid approach also stands out as a promising direction for future research. Finally, the development of software to facilitate the application of the proposed model is another important future research direction.

Author Contributions

Conceptualization, M.A. and V.P.; methodology, M.A. and V.P.; software, M.A. and V.P.; validation, M.A. and

V.P.; writing—original draft preparation, M.A. and V.P.; writing—review and editing, M.A. and V.P. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflicts of Interest

The authors declare no conflict of interest.

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