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DOCTORAL THESIS

DEVELOPMENT OF AN INTEGRATED SYSTEM FOR OPTIMIZING OPERATIONAL PROCESSES AND MONITORING OF WORK SYSTEM COMPONENTS

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Foreword

This doctoral thesis, entitled *"Development of an integrated system for optimizing operational processes and monitoring of work system components",* addresses the issue of occupational safety and health from a systemic and digitized perspective, by designing and substantiating an integrated online OSH system, adapted to the requirements of contemporary organizations.

In the context of the intensification of digitization processes and the increase in legislative and organizational requirements regarding the protection of workers, OSH activity can no longer be treated exclusively as a formal or administrative obligation, but must be organically integrated into the organization's operational processes. Starting from this premise, the present research aims to provide a conceptual and applicative framework through which the management of occupational risks, the monitoring of work factors and the optimization of operational processes are correlated in a unitary, accessible and functional information system in the online environment.

The motivation for the elaboration of this thesis derives from the practical experience gained in the field of OSH and from the observation of the existence of frequent malfunctions in the management of documentation, risk assessment, training of workers and monitoring of performance indicators in the field of occupational safety and health. The need for an integrated tool, capable of centralizing, analyzing and optimizing these activities in real time, was the starting point of the scientific approach.

The doctoral program consisted of preparing, presenting and defending scientific exams and reports, deepening the study, proposing and developing its own conceptual framework that integrates operational performance, ergonomics and prevention of occupational risks in a unitary optimization system, the realization and publication of scientific papers, as well as the elaboration of the present doctoral thesis.

The realization of this work was possible thanks to the support and careful guidance of the scientific coordinator, ***Mrs. prof.univ.dr.ing. Oana- Roxana CHIVU***, who constantly led me to look for new approaches regarding the design, development and validation of an integrated web platform for the management of Occupational Health and Safety activities, accepting to be my mentor and guide me throughout the preparation of my doctoral thesis. I would like to thank her in particular for her valuable advice and for sharing knowledge in the field of OSH, for supporting me whenever I needed it or when I faced various problems during my research.

I also thank the members of the steering committee, *Assoc. Prof. Dr. Ing. Claudia Borda* and *Sl. Dr. Eng. Marilena Gheorghe,* for the ideas provided during the period of preparation of the doctorate and the elaboration of the thesis.

Equally, I would like to thank the scientific researcher *Alina Trifu* for her support and guidance in the process of publishing scientific articles.

Last but not least, I thank *my parents* for always believing in me and providing me with support and moral support throughout the preparation of my doctoral thesis. The support and encouragement of my family meant a lot to me and I am grateful to have you by my side in this challenging and rewarding endeavor.

Andrei Ştefan IACOB

Introduction

The integration of the principles of modern risk management with advanced digital tools offers the opportunity to develop intelligent systems capable of monitoring in real time the components of the work system: the worker, the equipment, the working environment, the workload and the information flows. Within this framework, this thesis proposes the development of an integrated online OSH system, oriented towards optimizing operational processes by permanently correlating prevention and protection activities with organizational performance indicators.

The research problem is based on the existence of a discontinuity between the operational activity and the management of occupational safety and health. Although the legislation imposes clear obligations on risk assessment, worker training, incident monitoring and compliance reporting, in practice these activities are often managed separately, without digital integration and without effective predictive analytics mechanisms.

The rapid transformations generated by digitalization, automation and Industry 4.0 require integrated approaches to operational process management. In practice, the planning, optimization and monitoring of the components of the work system are often treated separately, which leads to losses in efficiency, suboptimal decisions and difficulties in adapting to changes. The development of an integrated system responds to this gap, providing a unitary framework for the coordination of human, technical and informational resources, with a direct impact on organizational performance.

The development of an integrated planning and optimization system, correlated with the continuous monitoring of the components of the work system, has the potential to generate original contributions both at a theoretical level, by extending existing models, and at a practical level, through direct applicability in industrial or service organizations. Such an approach supports the current objectives of operational efficiency, reduction of resource consumption, improvement of working conditions and increased sustainability of processes.

* * *

The doctoral thesis is organized in two main parts: the current state of research and contributions on *the Development of an integrated system of planning, optimization of operational processes and monitoring of the components of the work system***,** and is structured in nine chapters, comprising 169 pages, 48 figures, 28 tables, 18 calculation relationships, 246 bibliographic sources, as follows:

Chapter 1 – "Integrating digitalization into occupational health and safety", addresses the current guidelines in defining the concept of OSH 4.0, the evolution of the digitalization process and the main components of the digital technologies used in OSH 4.0. The results of this chapter substantiate the need to explore advanced risk assessment methods capable of processing the data flows generated by these new intelligent systems.

Chapter 2 – "**State of play in the development of OSH monitoring systems in the field of transport",** presents some aspects related to risk management in the field of road transport, considerations regarding the implementation of the new OSH monitoring systems , as well as aspects related to complex and outdated legislation, lack of adequate standards, cost implications related to the development of new technologies.

Chapter 3 - ”**Conclusions on the state of research on the integration of fundamental principles and processes of digital transformation in the field of occupational safety and health**” , includes a number of important conclusions drawn from the analysis of the current state of research and development in the field, including an analysis of current trends regarding the development of decision-making tools to support operational management in conditions of increased uncertainty and dynamism.

The second part of the doctoral thesis is dedicated to the presentation of contributions regarding the development and implementation of an integrated system for optimizing operational processes and monitoring of work system components.

Chapter 4 includes **the "Directions, main objective and methodology of research and development"** used in this doctoral thesis.

Chapter 5 – "**Contributions regarding the development of an integrated system for planning and optimization of operational processes and monitoring of work system components - OSH Online**"It starts with the overview of the intelligent, cloud-native, and fully integrated platform designed to automate work

processes, support real-time compliance monitoring, and provide full traceability of actions and responsibilities. The originality of the proposed system lies in the integration of emerging technologies, Artificial Intelligence, telematics, VR, in a single unified platform. OSH Online introduces a tightly connected framework that combines real-world operational data with tailored safety interventions and comprehensive coverage of OSH requirements. The last sub-chapters include contributions from the perspective of human resources management, the platform providing a coherent framework for employee management, data import and validation, electronic signing of OSH/SU sheets and digital archiving of documents with legal value. Secure authentication (email/password, OTP, 2FA), action logging, and granular access control functionalities ensure compliance with data protection and information security requirements.

Chapter 6 – "**Contributions on the analysis and optimization of OSH processes through the Functional Resonance Analysis Method. Comparative Synthesis: Traditional Process vs. Integrated Digital Process***",* includes in-depth analysis of the occupational safety and health training process in the road transport industry, by applying **FRAM.** A key result of the research is to demonstrate that the traditional OSH training system is structurally fragile. Digital transformation, based on FRAM modeling, is not only a technological option, but a strategic necessity for increasing organizational resilience, efficiency and compliance in the road transport industry. Thus, the thesis validates the hypothesis that the digital integration of OSH training processes reduces negative variability, strengthens traceability and transforms the system into an adaptive, robust and sustainable performance-oriented one.

Chapter 7 **– "Contributions to the evaluation of the effectiveness of OSH training in three road transport companies where the integrated digital platform was implemented"** presents the Kirkpatrick model, internationally recognized as one of the most widely used conceptual frameworks for the analysis of the effectiveness of training programs, applied comparatively in three road transport companies with different organizational profiles, in which the SSM-Online platform was implemented.. The Kirkpatrick model applied in a digital context provides a valid and replicable framework for the evaluation of road transport training, confirming that the platform developed within the thesis meets the criteria of novelty, practical applicability and scientific value, contributing to the development of the concept of Safety 4.0 – a smart, integrated and sustainable approach to occupational safety and health.

Chapter 8 – *"***Contributions to the development and validation of a FRAM-Kirkpatrick hybrid framework for assessing the effectiveness of digital OSH training in complex socio-technical systems**", includes the doctoral student's work to demonstrate that the effectiveness of training in complex socio-technical systems cannot be meaningfully assessed without a systemic perspective, which is why it proposes the development of a FRAM-Kirkpatrick framework, which integrates Functional Resonance Analysis Method (FRAM) with the Kirkpatrick Training Assessment Model. The FRAM-Kirkpatrick framework developed is applied through a multiple case study in the road transport sector involving three companies and 47 professional drivers. The results show significant improvements in learning and safe behavior, accompanied by a substantial reduction in functional variability within critical system functions.

Chapter 9 – "**Final conclusions and main contributions to the development of an integrated system of planning and optimization of operational processes and monitoring of the components of the work system**" are presented the final conclusions of the research results, the personal contributions made in the field studied and the development directions for future research. The results obtained have the potential to be disseminated through scientific publications and can be the basis for the development of good practice guides in the field of optimization of industrial processes with the integration of health and safety at work.

The scientific importance of this doctoral thesis is supported by the contributions made to the streamlining and automation of the HSM, SU, RSVTI and HR processes, reducing the risk of accidents at work through rigorous planning, periodic checks and proactive monitoring, increasing traceability, accountability and transparency through a complete and adaptable digital platform.

The practical importance of this doctoral thesis lies in the fact that the proposed digital platform , OSH Online, can be adapted and implemented in various fields of activity, such as industry, services or public administration. Its impact lies in increasing the competitiveness of organizations and improving working conditions.

Legend

Crt. no.	Abrev.	Signification
1.	AMS	Spinal muscular atrophy
2.	API	Application Programming Interface
3.	THE	Realitatea augmentată / Augmented Reality
4.	CCTV	Televiziune cu Circuit Închis / Closed-Circuit Television
5.	CI	Identity card
6.	CMS	Content Management System
7.	COLOR	Classification of Occupations in Romania
8.	NOC	Personal numeric code
9.	DMS	Document Management System / Document Management System
10.	ECM	Electronic Control Module
11.	EIP	Personal protective equipment
12.	ERP	Enterprise Resource Planning
13.	ESENER	Sondajul european în rândul întreprinderilor privind riscurile noi și emergente/ European Survey of Enterprises on New and Emerging Risks
14.	EU-OSHA	European Agency for Safety and Health at Work
15.	FRAM	Functional Resonance Analysis Method / Functional Resonance Analysis Method
16.	GDPR	Regulamentul General privind Protecția Datelor /General Data Protection Regulation
17.	GPS	Global Positioning System
18.	HR	Resurse Umane / Human Resources
19.	HRM	Human Resource Management
20.	IA	Artificial intelligence
21.	ID	Personal identification code
22.	IoT	Internet of Physical Devices / Internet of Things
23.	EN	Information technology
24.	ITS	Sistemele inteligente de transport/ Intelligent Transport Systems
25.	LMS	Learning Management System
26.	ML	Machine learning /Machine learning
27.	ORM	Object-relational Mapping / Object Relational Mapping
28.	OTP	Parolă unică / One Time Password
29.	PDI	Integrated digital platform
30.	PM	Environmental Protection
31.	PT	Traditional process
32.	REST	Representational State Transfer
33.	RFID	Radio Frequency Identification Technologies
34.	RPA	Robotic Process Automation
35.	RPC	Apel de procedură de la distanță / Remote Procedure Call

36.	RTLS	Sisteme de localizare în timp real/ Real-Time Location Systems
37.	RSVTI	Responsible for the Supervision and Technical Verification of Installations.
38.	SLA	Service Level Agreements
39.	Smart PPE	Echipament Individual de Protecție Inteligent/ Smart Personal Protective Equipment
40.	SSL	Secure Internet Communication Protocol /Secure Sockets LayeR
41.	SSM	Occupational safety and health
42.	TSI	Intelligent Transport Systems
43.	ON	Emergency situations
44.	ICT	Information and Communication Technology
45.	TLS	Securitatea stratului de transport /Transport Layer Security
46.	TMS	Transport management systems
47.	UAS	Unmanned Aircraft System
48.	UAV	Aeronavă fără pilot la bord / Unmanned Aerial Vehicle
49.	VR	Virtual Reality
50.	WRMSD	Work-Related Musculoskeletal Disorders/ Work-Related Musculoskeletal Disorders
51.	WSGI	Web Server Gateway Interface and Application / Web Server Gateway Interface
52.	WSN	Rețea fără fir de senzori / Wireless Sensor Network

Chapter 1. Integrating digitalization into occupational health and safety

1.1.Introduction

In industries characterized by high dynamism, such as cargo transport, digitalization is becoming a strategic priority due to the increased requirements for transparency, accuracy and availability of information. The integration of organizational applications and the interconnection of customer and supplier systems allow data to be centralized in a unified platform, facilitating the traceability of operations and supporting rapid decisions.

Digital transformation is described as a process that goes beyond the adoption of software tools, fundamentally influencing the interaction between the employee and the work environment. In OSH, this evolution supports the transition from a reactive management (focused on the analysis of the incidents produced) to a proactive and predictive model, in which hazards can be identified before accidents materialize.

1.2. Integrating digitalization into occupational safety and health

OSH is defined as a proactive and multidisciplinary field, oriented towards hazard identification and risk control, with the objective of protecting employees and ensuring the continuity of the organization [H09]. However, the digitalization of OSH processes does not produce immediate effects on overall performance, as the technologies brought together under the concept of OSH 4.0 function as support tools for optimizing existing activities and reducing risks. [S10]

While digitalization creates many opportunities, it also brings a number of new challenges [Q04]. In the course of this process, legal gaps in the field of OSH began to emerge, in particular in relation to new forms of work organization and the use of advanced technologies [E14]. This study aims to analyse the integration of digitalization in OSH, as well as the favourable and unfavourable effects on working life and employees.

Monitoring devices integrated into smart personal protective equipment enable real-time surveillance of hazards in the work environment, generating early warnings of harmful exposures. At the same time, they can provide personalized recommendations in real time, with the aim of influencing employee behavior and improving the level of occupational health and safety [T04, C19].

Therefore, the integration of digitalization into OSH is treated as a critical necessity for the protection of life, business continuity and adaptation to dynamic occupational risks, which evolve with technology.

1.3. The impact of digitalization on occupational safety and health

Based on the literature analysed, the main challenges of digitalization for OSH are summarised: insufficient regulation for the safe integration of complex technologies; eliminating the time and space constraints of work and the pressure of permanent availability, which complicates the inspection and control of OSH; low level of managerial awareness and inadequate risk assessments in digitized processes; overexertion and increased cognitive effort, with effects on involvement and well-being; difficulties in internal collaboration and ambiguities regarding responsibilities in new digital processes; transparency deficiencies and vulnerabilities in data protection and information security.

In order to mitigate these challenges, the following courses of action can be proposed: establishing an ethical framework and behavioural norms for digitalization; developing and updating the regulatory framework on OSH obligations and responsibilities; continuous training and two-way exchange of knowledge; reorganising OSH services to cover new forms of work; actively involving employees in digitalization strategies; adopting a user-centric "design for prevention" approaches; carrying out comprehensive risk assessments; strengthening the culture of security. The effective integration of contemporary technologies into OSH is conditional on a multidisciplinary approach and cooperation between academia, industry, social partners and authorities, and EU-OSHA's involvement in research on the relationship between digitalization and OSH is also mentioned. [C19, A18]

1.4. Smart digital systems

Smart digital systems have developed a lot with the fourth industrial revolution. The rapid development and improvement of digital systems and technologies has stimulated the development of new occupational health and safety monitoring systems, thus helping organizations to ensure an effective level of safety for workers.

An informative study was carried out in order to identify the degree of integration of digital systems within the organizations in Romania, the share of the integration of digital systems in the analysed companies is presented in Fig.1.3.-Fig.1.6.

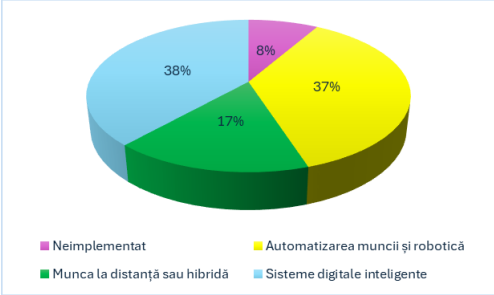


Fig. 1.3. The share of digital systems integration in large companies.

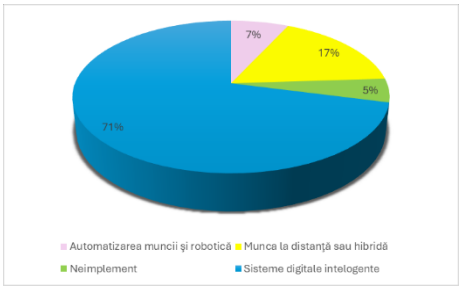


Fig. 1.4. The share of digital systems integration in medium-sized companies.

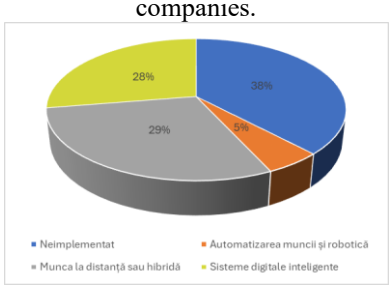


Fig. 1.5. Share of digital systems integration in small businesses.

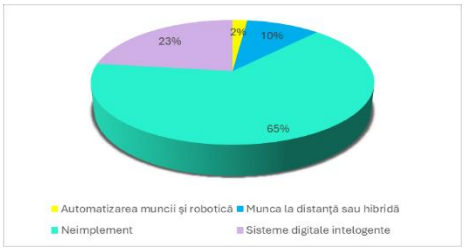


Fig. 1.6. Share of integration of digital systems in micro-enterprises.

The success of integrating digitalization into occupational health and safety depends on a fragile balance between technological advancement and the human factor. The results of this chapter substantiate the need to explore advanced risk assessment methods, capable of processing the data flows generated by these new intelligent systems, a topic that will be detailed in the following sections of the paper.

Chapter 2. State of play in the development of OSH monitoring systems in the transport sector

2.1. The importance of transport

Transport plays an essential role in the functioning of the economy, in its absence human activities being difficult to organize and carry out. The population's access to goods and services is possible, to a large extent, thanks to technological development in the field of transport. Transport is an integral component of the cost of products, and the continuous improvement of transport technologies has led to the reduction of these costs and the expansion of access to goods for a greater number of users.

2.2. Road transport in the European Union and Romania

At European Union level, around 44% of freight transport is carried out by road, compared to 39% by short sea shipping, 10% by rail and 3% by inland waterways. As regards passenger transport, road transport accounts for around 81%, while rail and air transport hold shares of around 6% and 8% respectively [B13].

In Romania, road transport is the main mode of transport, both for the movement of people and for the transport of goods. Its share on the interurban and international transport market is dominant, reaching values of approximately 81.69% in the case of freight transport and 78.37% in the case of passenger transport. The evolution of road traffic at national level highlights a sustained growth trend; Thus, the average number of standard vehicles was estimated at about 11,000 in 2015, and will reach about 50,000 standard vehicles in 2030.

2.3. Intelligent transport systems

Through the use of digital technologies, the components of the transport system can acquire intelligent characteristics, through the integration of microchips, sensors and communication devices, which allow data to be collected, processed and transmitted in real time.

Intelligent Transport Systems *(ITS*) can be defined as sets of advanced applications that integrate communication, electronics, navigation and information processing technologies, with the objective of optimizing the operation of existing transport systems. ITS-specific applications include advanced traffic management systems, passenger information systems, electronic toll systems, advanced vehicle control systems and smart public transport solutions [S09].

2.4. Main OSH challenges for drivers

In the organizational practice in Romania, a number of recurrent deficiencies in the application of OSH requirements for drivers have been identified over time. These deficiencies can have significant consequences for both worker safety and companies' performance and legal liability.

Regulation (EC) No 561/2006 and the European Agreement on Crew Work set clear limits on driving times, breaks and rest periods, with the aim of preventing fatigue and reducing the associated risks. In addition, advanced driver assistance technologies, such as automatic emergency braking, lane departure warning and blind spot monitoring, can contribute substantially to reducing the risk of accidents and increasing the overall level of safety in vehicle operation.

2.5. Neglect of Periodic Training

Another frequently encountered deficiency in the field of occupational health and safety is the lack of adequate periodic training programs for drivers. Regular training programs are not only meant to refresh the information already acquired, but also to raise awareness of new or emerging risks.

A common deficiency in occupational health and safety management for drivers is the performance of incomplete or strictly formal medical evaluations.

To ensure effective communication in the field of occupational safety and health, it is necessary to implement well-structured strategies and practices. The implementation of anonymous feedback mechanisms, such as online questionnaires or suggestion boxes, encourages honest reporting of problems without fear of sanctions, favouring the rapid identification of shortcomings and the adoption of appropriate corrective measures.

2.6. OSH monitoring systems

The present study aims to identify the main types, purposes and areas of use of smart digital OSH monitoring systems. At the same time, the analysis aims to assess the opportunities, risks and challenges associated with the implementation of these systems, in order to improve the OSH level of workers [A12]. The data suggest that new OSH monitoring systems are still in their infancy in some cases, but that the trend is towards increased adoption due to increased awareness of old and new OSH needs compared to the recent past and due to the improved opportunities offered by technological sophistication.

The new OSH monitoring systems are defined as sets of solutions that use digital technologies to collect and analyse data, to identify and assess occupational risks, to prevent and/or minimise harmful effects on workers, and to promote a high level of occupational safety and health. These technologies include, but are not limited to, information and communication technology (ICT), monitoring cameras, artificial intelligence (AI), augmented and/or virtual reality (AR/VR), the Internet of Things, large-scale connectivity and big data applications, wearables, smart clothing and personal protective equipment, exoskeletons, unmanned aerial systems (UAVs/UAS), as well as radio frequency identification (RFID) technologies.

Two major general approaches to new OSH monitoring systems can be identified in the literature and current practice: (i) a **proactive** approach, oriented towards injury prevention and health promotion; and (ii) a **reactive** approach, focused on accident and emergency management. These new systems can support inclusion and diversity, help workers find and stay in work, and facilitate health and protection from workplace injuries.

2.7. Use of the main OSH monitoring systems

2.7.1. Proactive OSH monitoring

It is organised for two main purposes: providing training to workers and identifying hazards, and early risk assessment to prevent injury. Injury can be prevented by real-time measurement of routine and non-routine harmful individual/collective exposure: heat, pressure, noise, dust, chemicals, biological agents, radiation, UV. Drones, sensor networks, AR, cobots, and AI can take on dangerous tasks of monitoring, maintaining, and repairing facilities and spaces, which can help reduce work stress or the consequences of accidents and injuries on mental health and wellbeing.

2.7.2. Reactive OSH monitoring

It is organised for two main purposes: minimising the consequences of accidents/emergencies and reporting and investigating accidents. When prevention fails, digital OSH monitoring systems and technologies enable employers to react quickly and effectively to emergencies, can help investigate the accident and provide information about where the accident occurred, who was present and who the victims were, what actions and/or conditions led to it, and what happened during the accident and subsequent rescue operations.

2.8. OSH monitoring and specific needs

OSH monitoring systems that send warnings not only through the use of acoustic alerts, but also through vibration or light present opportunities for workers with hearing impairments and can also be more effective for all workers in workplaces with high noise levels. In addition, migrant workers with low language skills may have easier access to videos and visual cues than to text – for example, when examining accidents recorded by cameras, in the context of training.

2.9. Risks and challenges of OSH monitoring systems

OSH monitoring systems can have adverse effects and sometimes a net negative impact. For example, exoskeletons present a number of potential risks. Human-machine interfaces (face, gestures, voice, eye movement, brain signals) could misinterpret altered or low-power signals – for example, due to dead batteries, interference, language and pronunciation problems.

Switching to algorithmic management can pose psychosocial risks due to the impact on working relationships, communication and trust. AI management can reduce contact between management and workers, as well as between colleagues.

Psychosocial risks could also explain the general reluctance of workers to introduce new systems to monitor OSH and those technologies in the workplace. In some cases, some systems are more acceptable than others.

Chapter 3. Conclusions on the state of research on the integration of fundamental principles and processes of digital transformation in the field of occupational safety and health

From the analysis of the current state of research and development in the field of integrated systems for optimizing operational processes and monitoring of work system components, important conclusions can be drawn, as follows.

- Road transport is one of the most important economic sectors in Romania, having a significant impact on mobility, trade and the national economy. Risk management in the field of road transport thus becomes a priority, given the significant number of traffic accidents and their impact on human lives, but also on the economy. (see § 1.1).
- OSH 4.0 is an emerging concept that aims to optimize the interaction between humans and machines by integrating the fundamental principles of Industry 4.0 and the digital transformation processes in the field of OSH. (see § 1.2).
- Smart digital systems have developed a lot with the fourth industrial revolution (Industry 4.0). The rapid development and improvement of digital systems and technologies has stimulated the development of new occupational health and safety monitoring systems, thus helping organizations to ensure an effective level of safety for workers (see § 1.4).
- In the road transport sector, paying close attention to working conditions is essential to prevent dangerous incidents and accidents, as well as to maintain an adequate level of worker satisfaction and motivation. The specific characteristics of this sector – permanent mobility, prolonged exposure to stressors and dependence on infrastructure – make accident risk management more difficult compared to other areas of activity. (see § 2.3).
- Another common shortcoming in the field of occupational health and safety is the lack of adequate regular training programmes for drivers. However, the continuous evolution of technologies, legislative changes and constant changes in traffic conditions require the knowledge and professional skills of drivers to be regularly updated (see § 2.4).
- New occupational safety and health monitoring systems have the potential to prevent injuries (including health problems) and minimise the consequences of an accident. In addition, they can have a positive

psychosocial impact related to: improving the OSH culture adapted to workers' needs, reducing stress and increasing the significance of the workplace. (see § 2.5.1).

- The digital technologies used by OSH monitoring systems offer various opportunities to improve OSH. Digital technologies, sensors and software are often used in combination in new OSH monitoring systems (see § 2.7).

The development of an integrated planning and optimization system, correlated with the continuous monitoring of the components of the work system, has the potential to generate original contributions both at a theoretical level, by extending existing models, and at a practical level, through direct applicability in industrial or service organizations.

Chapter 4. Directions, main objective and methodology of research and development

4.1. Research and development directions

Based on the analysis of the current status, the following directions of research and development regarding the development of an integrated system for optimizing operational processes and monitoring of the components of the work system are considered to be topical:

• identifying concrete solutions to issues such as: sustainable development of human resources management to ensure the development of workers' skills, stimulating creativity, digitization skills and their motivation;

• addressing identified challenges and risks and maximising opportunities, which depend to a large extent on how technologies are used, managed and regulated;

• identifying the consequences (positive or negative) on the safety and health of workers, which the implementation of digital systems entails, based on data analysis and scientific literature;

• the impact of the integration of these systems on the safety and health of workers.

4.2. Main objective of the research and development activity

The main objective of the doctoral activity was the creation and implementation of a digital platform, which would contribute to increasing efficiency, productivity and organizational flexibility, aiming to:

- Streamlining and automating HSM, SU, RSVTI and HR processes.
- Reduce the risk of workplace injuries through rigorous planning, regular checks and proactive monitoring.
- Increasing traceability, accountability and transparency through a complete and adaptable digital platform.

The analysis of the research and development directions led to the establishment of the following specific objectives, in order to achieve the main objective proposed of the doctoral thesis:

- analysis of concepts and methods for optimizing operational processes;
- identifying and evaluating existing inefficiencies in the analysed processes;
- defining the relevant performance indicators for the work components;
- Demonstrating the vulnerabilities of traditional OSH management methods with the help of FRAM;
- Creating a complete integrated digital platform that is adaptable to different organizational contexts;
- implementation of the designed system, application of the FRAM–Kirkpatrick hybrid framework in three road transport companies;
- testing and validating the efficiency of the proposed system in the digital training process in complex socio-technical systems.

In conclusion, the topic of the doctoral thesis on the development of an integrated system for planning and optimizing operational processes, correlated with the monitoring of the components of the work system, proves to be necessary and timely in the current context of increasing complexity and dynamism of the organizational environment.

4.3. Research and development methodology

The R&D methodology is conceived as an original system for analyzing and optimizing operational processes, centered on the human-system-environment interaction. The methodology includes clear steps to identify occupational risks, ergonomic assessment and correlate them with operational performance indicators, in order to achieve the main objective of the doctoral activity, as well as future developments.

The proposed research has an applicative and interdisciplinary character, combining elements from the field of process management, industrial engineering, labor analysis and information systems. The methodological approach is mixed, including:

- theoretical research, through the analysis of specialized literature;
- qualitative research, through case studies, direct observations and interviews;
- quantitative research, through the collection and analysis of operational data.

This approach allows for a deep understanding of the existing processes and the scientific substantiation of the proposed optimization solutions. The methodology is structured on several successive stages:
Stage 1 – Literature review
Step 2 – Analysis of existing OSH processes and risks
Step 3 – Data collection and processing
Step 4 – Design of the optimization system
Step 5 – System Testing and Validation

The proposed research methodology provides a coherent and rigorous framework for the development of a system for optimizing the operational processes of the work components. By combining theoretical analysis with applied research, the thesis aims to obtain relevant results both from a scientific and practical point of view, contributing to the efficiency of organizational activities and to supporting the decision-making process.

Chapter 5. Contributions regarding the development of an integrated system for planning and optimization of processes and monitoring - OSH Online

In high-risk areas such as road transport, conventional paper-based or semi-digital approaches to occupational safety and health management are insufficient [I05, I06]. To address these challenges, OSH Online is proposed as an intelligent, cloud-native, and fully integrated platform designed to automate work processes, support real-time compliance monitoring, and provide full traceability of actions and responsibilities [I07, I09].

5.1. Description of the platform

5.1.1. General description

OSH Online is an integrated web platform for managing Occupational Health and Safety, Emergency Situations, Environmental Protection and Human Resources activities. The system has been designed to provide a unified and scalable solution, capable of meeting the requirements of organizations of any size, including those with a multi-site, multi-user and multi-lingual structure. [I09]
The application is developed in a cloud-based regime, being accessible directly from the browser, without local installations. The graphical interface is intuitive, responsive and adapted for use on desktop, tablet and mobile devices, providing a seamless experience regardless of the environment.

5.1.2. General architecture and stratification

The Online OSH platform is developed in the Python language, following the principles of the three-tier architecture, structured on three main layers:

1. Presentation / User Interface - represents the user interface, implemented in modern web technologies (HTML5, CSS3, JavaScript, responsive frameworks).
2. Application / Workflows (Server + Module) - the intermediate layer that manages application logic, business rules and communication mechanisms between users and the database.
3. Data / Persistence (PostgreSQL + Security Mechanisms and Integrations) - the data persistence layer, built on a robust PostgreSQL foundation, with support for secure transactions, column-level encryption and replication.

Through this layered and modular architecture, OSH Online provides a solid foundation for expanding future functionalities, integrating with emerging technologies, and supporting digital compliance processes in modern organizations.

5.1.3. Components and technologies

The system structure is based on a three-tier architecture, which clearly separates the levels of interaction with the user, application logic and data persistence, on top of which two transversal layers are superimposed: security & compliance and external integrations. The UI layer provides mechanisms for customizing the experience, allowing each user to set up their own dashboard, define quick filters, or set visual notifications based on their responsibilities.

The application layer is the functional core of the system, where logical processes, decision-making flows, and automated actions take place. It is implemented in Python, a programming language recognized for its stability and clarity. At its core is the application engine, built on a Python framework equipped with ORM (Object Relational Mapping), which facilitates secure and abstract interaction with the database.

5.1.4 Communication flows and protocols

The operation of the Online OSH platform is based on a carefully designed system of communication flows, which ensures the secure, coherent and efficient exchange of information between its internal components and external systems.

Communication between the user and the system takes place through the web browser, using the standard HTTP and HTTPS protocols. All requests from the client are routed to the application's core, which processes the requests and returns responses in structured formats, such as JSON-RPC or XML-RPC. The system is designed to run in a multi-worker/multi-threaded architecture, where multiple instances of the application work simultaneously, handling requests, cron tasks, and automated processes. In this way, OSH Online can simultaneously process requests from dozens of users modifying the same tables, while still maintaining the integrity and consistency of the database.

5.1.5. Scaling, performance and distribution

The Online OSH platform has been designed to work efficiently both in small production environments and in complex infrastructures, distributed nationally or internationally. To ensure consistent performance, stability and high availability, the system adopts modern principles of horizontal and vertical scalability, supported by load balancing, replication and automatic recovery in the event of a failure.

5.2. Functional innovation and contribution to the current state of the field

The originality of the proposed system lies in the integration of emerging technologies, Artificial Intelligence, telematics, VR, in a single unified platform. OSH Online introduces a tightly connected framework that combines real-world operational data with tailored safety interventions and comprehensive coverage of OSH requirements.

(1) Integration of telematics and sensor data. The platform receives continuous streams of telematics data for vehicles (GPS, tachographs, fatigue and stress sensors). This data is used by a rules-based engine and machine learning to dynamically adapt safety training.

(2) VR-based immersive training. Critical scenarios, collisions, fire emergencies are reproduced in interactive VR modules. This approach transforms passive training into experiential learning, improving knowledge retention and situational awareness.

(3) Artificial intelligence-based digital assistant. A recommendation engine analyses training history, telematics profiles, and regulatory requirements to generate individualized training plans and forecast compliance risks.

(4) Real-time digital auditing. The platform automatically detects missing or expired registrations, inconsistencies, and deviations from legal requirements. The platform also generates automatic alerts and ready-to-submit compliance reports.

(5) Transnational accessibility. Through multilingual interfaces, machine translations, voice guidance, and visual learning tools, the platform is usable by drivers and foreign workers with low digital literacy.

5.3. Basic functionalities of the platform

OSH Online integrates an extensive suite of operational modules that together provide a complete, end-to-end management of OSH activities. Each module is designed to automate administrative tasks, ensure full compliance with legal requirements, and support real-time decision-making in complex organizational environments. The main module is the Centralized Personnel Management module, which automatically synchronizes employee data via REST/JSON interfaces with existing HR systems.

Training and skills development are addressed through a robust digital training suite, which offers thematic instructional videos, online assessments, adaptive learning streams, and long-term digital storage of individual training recordings.

By integrating these functionalities, the platform provides a complete dashboard for OSH compliance, reduces administrative burden, and ensures the permanent availability of critical documents. OSH Online is a state-of-the-art digital ecosystem that combines OSH training, telematics, immersive learning, automated compliance, and real-time operational data. Its cloud-native architecture, advanced automation, and integration

of emerging technologies provide a robust, scalable, and intelligent solution tailored for high-risk sectors such as road transport.

5.4. Employee administration in the dedicated OSH/HR platform online

5.4.1. Access to the SSM-SU platform

Access to the secure platform is made using either the e-mail address or the personal identification number (CNP). If the user does not have a declared email address, it is mandatory to fill in the mobile phone number, as all subsequent communications will be transmitted exclusively by SMS.
The choice of the company is made easily, from a list visible after authentication, example in fig.5.3.
To access the personal account details, the user needs to select the **Your Account** option in the upper right corner of the interface (fig.5.4.). This section provides access to personal information and allows the management of account settings (employees, OSH/SU sheets, signatures).

After logging in, the user can navigate to the "Employees" section of the main menu. Each employee has an associated management action that allows them to edit their data or view additional details, such as qualifications, authorizations and OSH/SU sheets.

5.4.2. Ways to introduce and edit employees

To manage users on the platform, there are two main methods:

1. Manual access through the platform interface
2. importing employees using Excel files

After filling in all the required fields, the user can save the information via the "Add Employee" button. This process ensures that both the direct boss and the OSH inspector verify and approve the employee's activity, according to internal and legal rules.
For bulk employee import, the user needs to access the "Employee Import" option. In this menu, you can upload an Excel file containing the necessary data to add several employees at once.

5.4.3. Viewing and signing OSH/SU sheets

The platform allows the management and signing of OSH/SU sheets in an efficient way, ensuring compliance with occupational safety and health regulations as well as emergency rules. Users can access and sign these sheets both for themselves and for the company's employees, through the platform's interface (fig.5.7).
Users can open each sheet to see specific details related to its content, including instructions on the necessary safety measures, applicable rules and other relevant information on occupational health and safety. Once the user has viewed the record, they can electronically sign the document to confirm that they have read and understood the OSH/SU requirements. The electronic signature is mandatory for the validation of the sheet, thus ensuring that all employees have been properly informed about the safety measures at work.

The platform also allows for the generation of detailed reports on the status of signatures and the progress of the completion of OSH/SU sheets, useful in case of inspections or audits. This functionality makes the management of OSH/SU sheets efficient and well organized, providing companies with a complete solution for complying with legal obligations and maintaining a safe and compliant work environment.

5.5. Employee administration in the dedicated OSH-SU platform OnlinePortal

The portal is a digital platform dedicated to training employees on workplace safety rules and procedures and emergency management [I10]. At the beginning of the collaboration, each employee receives an activation email for access to the platform. This email contains a link to set the personal password required for login.
In the next step of the process of enrolling in the training platform in the workplace safety regulations, the employee must add their first electronic signature. This is a final stage, through which the employee expresses his consent and assumes the commitment to follow the courses and to comply with the safety rules at work and to familiarize himself with how to sign the sheets. After the employee has completed their profile and signed, the next step is to access the courses available on the occupational safety and health training platform.
The steps required to view courses are:
Accessing the "Courses" section:

- On the platform's main menu, at the top of the page, select the **"Courses" option**.
- This will take you to the page where the courses available to you are displayed.

Course view:

- On the "My courses" page, search for the course you want. In this example, the course **"General OSH Introductory Training" appears**

- Click on the desired course to begin the training.

Navigating:

- Once you have selected a course, you will be able to access the training materials. Follow the directions in each section to complete the modules and assimilate the information presented.

At the end of the training process in the portal, the employee must confirm that he has completed all the necessary modules and that he is familiar with the occupational health and safety rules by signing the periodic training sheet. After completing the course modules, the last section of the left-hand menu usually contains the page intended for signing the training sheet.

5.6. Conclusions

A first major result of the research is the definition of a scalable technical architecture, based on the three-tier model, which clearly separates the presentation layer, the application layer and the data layer, complemented by transversal layers dedicated to security and external integrations.

A second contribution element is the modelling of end-to-end operational flows, which transform OSH processes from reactive activities, triggered by incidents or controls, into proactive processes, continuously monitored and supported by automated notification, validation and reporting mechanisms.

The originality of the system is highlighted by the integration of emerging technologies into a unified platform. The introduction of telematics data and sensors (GPS, tachographs, fatigue indicators) allows the correlation of operational behavior with training needs. The proposed platform also introduces a real-time digital audit model, where documents, OSH/SU sheets, authorisations and deadlines are continuously monitored.

Chapter 6. Contributions on the analysis and optimization of OSH processes through the Functional Resonance Analysis Method. Comparative Synthesis: Traditional Process vs. Integrated Digital Process

The application of FRAM (Functional Resonance Analysis Method) in the present research has the role of highlighting the vulnerabilities of the traditional OSH training process in the road transport industry, where the trainings are carried out, in most cases, face-to-face, and the related documentation is kept exclusively on paper. This methodological framework provides a realistic picture of the current limitations and is the starting point for justifying an integrated digital platform (SSM_Online Platform) that reduces undesirable variability and increases organizational resilience.

6.1. Analysis of the traditional OSH training process through the Functional Resonance Analysis Method

6.1.1. Description of the FRAM method and the traditional training process

Unlike classical risk analysis methods, which are based on linear causalities and error-effect relationships, FRAM addresses complexity by identifying the essential functions of a system and characterizing their interactions [H02].

The FRAM method is based on the definition of the essential functions of the system, each function being characterized by six fundamental aspects [H04]:

- Inputs (I) – what triggers the function;
- Results (O) – the result of the function;
- Preconditions (P) – the conditions that must be met before the function is performed;
- Resources (R) – what is needed for the function to be performed;
- Control (C) – the mechanisms that govern and regulate the function;
- Time (T) – temporal constraints.

6.1.2. Step I. Identification and description of the essential functions of the system

For the traditional OSH training process in road transport, the following essential functions have been identified (Fig. 6.1).

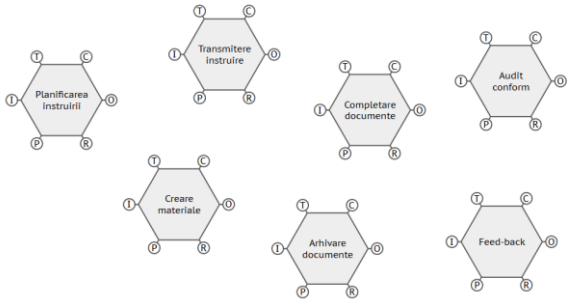


Fig. 6.1. Essential functions of the traditional training process (initial phase - identification), created with the help of the FRAM Model Visualizer software

6.1.3. Stage II – Characterization of function variability

The functional analysis carried out by the FRAM method highlights the fact that, in practice, each function of the OSH training system presents a certain degree of variability, influenced by organizational, human and contextual factors. Their cumulative interaction can generate negative functional resonances, i.e. systemic disruptions that affect the coherence, efficiency and compliance of the process. Therefore, the traditional OSH training system, based on manual processes and physical documents, is structurally vulnerable, and digitization and process integration become essential to reduce variability and increase organizational resilience.

6.1.4. Stage III. Determination of functional resonances

Functional resonance occurs when the variability of several functions combine, amplifying the effects. The FRAM method highlights not only the isolated functions of a socio-technical system, but especially how they influence each other. The present analysis identified five major types of resonances (R1–R5), which constitute the main systemic vulnerabilities.

Resonance R1 – "Delay in planning → missing signatures → non-compliance". If the planning is not carried out on time, the trainings are carried out late or in partial series. This leads to situations where some of the employees do not attend the scheduled session and remain untrained during the reference period.

Resonance R2 – "Outdated materials → irrelevant training → formal audit". In the traditional system, materials are printed and distributed by hand. If legislative changes occur in the meantime, they must be quickly integrated into the content.

Resonance R3 – "Large volume of paper and errors → opaque archive → impossibility of proof". The documentation of OSH trainings generates a large volume of paperwork: individual sheets, registers, participation reports. In the traditional system, all of this is kept in physical folders. The final effect: long audit delays, risk of penalties for missing documents, loss of trust in the record system.

Resonance R4 – "Fluctuations in attendance → ad-hoc recoveries → degradation of the quality of training". Drivers are often on the route when trainings are scheduled. Thus, participation in face-to-face sessions is highly variable. The bottom line: the quality of training is steadily decreasing, workers are not retaining essential information, and traffic risks remain high.

R5 Resonance – "Key Person Dependency". In many road transport companies, the entire responsibility for OSH lies with a single person. This is a typical resonance for organizations with limited resources: reliance on a single individual makes the entire system fragile and easy to destabilize. The end effect: high operational vulnerability, systemic risk and the impossibility of maintaining the continuity of the training and documentation process.

6.2. Analysis of the potential integrated digital OSH training process

FRAM's analysis of the integrated digital platform shows that variability, far from being a source of errors, is now becoming a factor of innovation and adaptability. Scheduling automation, centralized updating, automatic document generation, VR training, and digital auditing create positive functional resonances that radically transform the OSH training process.

6.3. FRAM Benchmarking: Traditional vs. Integrated Digital Process

The application of the FRAM method to the two scenarios – PT (traditional process, face-to-face, paper documents) and PDI – highlighted fundamental differences in the way the OSH training system works (Table 6.3.). The analysis of OSH training processes in road transport companies, carried out using the FRAM method, showed two contrasting pictures. The first image, that of the traditional process (PT), is characterized by

fragility, uncontrolled variability, and negative functional resonances. The second image, that of the integrated digital process (IDP), reveals a robust architecture with positive functional resonances that support not only legal compliance, but also long-term organizational performance.

Table 6.3. Comparative synthesis – Traditional vs. Digital

FRAM function	Traditional System (PT)	Integrated Digital System (PDI)
Training Planning	Manual, dependent on the OSH manager; Frequent delays	Automatic, calendar and notifications generated; Flexibility for all employees
Training materials	Printed, slow updating; Multiple parallel versions	Centralized, unique; Instant update and digital distribution
Streaming content	Face-to-face; Variable participation (drivers on races)	Online/VR, available 24/7; Access from anywhere, high participation
Rating	Written tests, manual correction, subjectivity	Digital tests, automatic correction, adaptive assessment
Documentation	Hand-filled sheets and registers; Transcription errors, missing signatures	Automatic generation of digital records and registers, electronic signature
Archiving	Physics, files that are difficult to manage; Risk of loss	Digital, secure, full traceability, instant search
Compliance audit	Periodic, difficult, based on incomplete documents	Continuous, digital, instant reports, real-time alerts
Feedback and improvement	Sporadic, informal, rarely capitalized	Systematic, AI-based; Personalized recommendations and dynamic update
Resonance Type	Negative: delays, errors, non-conformities	Positive: efficiency, compliance, resilience

This comparative section has the role of synthesizing the results of the two analyses and showing how digitization is not only a technological option, but a real structural redesign of the training and document management system.

6.4. Conclusions

The research in this chapter aimed at an in-depth analysis of the OSH training process in the road transport industry, by applying the Functional Resonance Analysis Method.

A key result of the research is to demonstrate that the traditional OSH training system is structurally fragile. Point adjustments cannot eliminate fundamental vulnerabilities because they are generated by the very architecture of the process.

From a theoretical perspective, the major contribution of the paper consists in the systematic application of the FRAM method in an insufficiently explored field – OSH training in road transport – and in demonstrating its usefulness as a strategic tool for organizational design, not just incident analysis.

From a practical perspective, the research provides a model applicable to road transport companies that want to modernise their OSH system. The implementation of an integrated digital platform leads to: reducing the risk of sanctions; optimizing the time allocated to administrative activities; increasing transparency and traceability; improving the quality of training; strengthening the prevention-oriented organizational culture.

In conclusion, the comparative analysis carried out demonstrates that the traditional OSH training process, based on physical documents and manual interventions, has significant structural limitations, which favor the appearance of negative functional resonances. Thus, the thesis validates the hypothesis that the digital integration of OSH training processes reduces negative variability, strengthens traceability and transforms the system into an adaptive, robust and sustainable performance-oriented one.

Chapter 7. Contributions on the evaluation of the efficiency of OSH training in three road transport companies where the integrated digital platform was implemented

In this chapter, the Kirkpatrick model is applied comparatively in three road transport companies with different organizational profiles: Company A - a large international logistics company, with about 1200 employees, Company B - a regional passenger transport operator, with about 250 employees, and Company C - a small short-distance freight transport company, with 40 employees. This selection allows the evaluation of the effectiveness of the integrated digital platform in various contexts, from complex, multi-site and multi-national

organizations, to micro-enterprises with limited resources. The benchmarking thus provides a clear perspective on the scalability, adaptability and real impact of digital OSH training in road transport.

7.1. Substantiation of the application of the Kirkpatrick Model for the evaluation of the effectiveness of the digital OSH training platform in road transport

The Kirkpatrick model has been adapted to multiple technological and cultural contexts, including e-learning trainings, leadership development programs, VR/AR trainings, but also technical areas, such as occupational safety and health. The application of the Kirkpatrick model in the research carried out in this doctoral thesis is justified by a number of reasons that reflect both the complexity of the training process in the field of occupational safety and health and the need for an objective assessment of the effects of the implemented digital platform.

7.2. Methodology applied in the evaluation

The evaluation of the platform was carried out through a phased process, covering all four levels of the Kirkpatrick model, using combined research tools: questionnaires, online tests, interviews, observations and analysis of organizational data. To ensure consistency of the analysis, the evaluation was carried out over an extended period, which included two distinct phases: a pre-intervention phase, of 12 months, in which baseline data were collected, and a post-intervention phase, with a duration of 24 months.

Table 7.1 Correlation between Kirkpatrick model levels and digital platform indicators

Kirkpatrick Level	Indicators measured in the platform / organization	Data source	Frequency
1. Reaction	Satisfaction, perceived usefulness, interactivity, degree of involvement	Online quizzes	After each module
2. Learning	Test scores, module progress, completion rate, VR performance	Digital platform	Automatic
3. Behavior	PPE use, respected breaks, preventive driving, daily checks	Observations, KPI managers	Monthly
4. Results	Number of accidents, lost days, fines, 100% compliance	HSM, HR, audit reports	Quarterly

By including all four levels of the Kirkpatrick model, the assessment provides a complete insight into the effectiveness of the platform: from learner reaction, to reinforcing safe behaviors, and ultimately improving organizational performance.

7.3. Level 1 – Learner satisfaction

To measure satisfaction in the three companies analysed, the digital platform used a standardized questionnaire applied at the end of each module. The questionnaire contained questions on a Likert scale (1 = "not at all satisfied", 5 = "very satisfied"), grouped on the following dimensions:

1. Relevance of the content ("The information was useful for my business").
2. Clarity of presentation ("The materials were easy to understand").
3. Interactivity ("I liked the presentation and the exercises").
4. Flexibility ("I was able to access training when I had time").

Perceived usefulness ("I believe that what I have learned will be useful to me").

The data was collected electronically and statistically analysed to identify general trends and differences between companies A, B and C. Comparing the three companies, we observe some clear trends (Table 7.3).

Table 7.3. Comparative results

Company	Traditional Training Satisfaction	Digital Training Satisfaction	Growth %
A (large)	58%	92%	+34%
B (average)	65%	88%	+23%
C (small)	55%	95%	+40%

Thus, level 1 of the Kirkpatrick Model confirms that the digital platform has generated a **major qualitative leap in employees' perception** of OSH training.

7.4. Level 2 – Knowledge acquired

The second level of the Kirkpatrick model is centered on measuring the actual learning that occurred as a result of the training. The proposed digital platform integrates two learning assessment mechanisms:

1. standardized online tests (with immediate feedback),
2. VR simulations and interactive scenarios, which measure the ability to apply knowledge.
3. Comparing the three companies, we see some clear trends outlined in Table 7.5.

Table 7.5. Comparative results

Company	Traditional Average Score	Digital Average Score	Growth %	Digital promotion rate
A (large)	58%	78%	+20%	85%
B (average)	72%	83%	+11%	92%
C (small)	40%	80%	+40%	95%

The results confirm the theoretical hypothesis: increased satisfaction (level 1) created favorable premises for effective learning (level 2). When employees perceived training as relevant and flexible, engagement increased, and assessment scores followed the same trend.

7.5. Level 3 – Behavior change

The third level of the Kirkpatrick model answers the question*: "Do participants apply what they have learned?"*tag. If level 1 (satisfaction) and level 2 (knowledge acquired) can be measured immediately after training, the change in behavior requires a period of observation to see if employees are actually changing the way they work. For the three companies analysed, behaviour change (Table 7.6.) was measured by a combination of:

1. *Direct observations from managers/supervisor/OSH manager* (checklists).
2. *Organizational KPIs (performance indicators)* (number of incidents reported, compliance with mandatory checks, use of equipment).
3. *Comparison of data before and after platform introduction*

In large companies (A), behavior change is harder to achieve, but the numerical impact is very high. In medium-sized companies (B), critical behaviors (passenger evacuation) have been greatly improved, which reduces the risk of serious incidents. In small companies (C), the change was rapid and spectacular, due to the direct manager-worker relationship (Table 7.8.).

The analysis of the three companies shows that the digital platform: causes significant increases in correct behaviors, reduces deviations (non-compliance with PPE, incomplete checks, procedural errors), stimulates proactive risk reporting. Thus, digital training does not stop at the level of "theoretical knowledge", but produces observable and measurable changes in employee behavior, which is the foundation for achieving level 4, organizational results.

Table 7.8. Summary of results

Company	Observed behavior	Result before platform implementation	Result after platform implementation	Change
A (large)	PPE compliance, emergency response	65% EIP compliance	90% EIP compliance	+25%
B (average)	Passenger evacuation procedures	60% correct application	85% correct application	+25%
C (small)	Daily vehicle checks	40% correct checks	85% correct checks	+45%

7.6. Level 4 – Organizational results

Level 4 of the Kirkpatrick model answers the question: "What concrete benefits does training have on the organization?". The three companies involved in the evaluation of the digital OSH training platform highlighted, through concrete results, the efficiency and adaptability of the system to the needs and particularities of each type of organization. Although the starting point and level of maturity in the field of occupational safety and health were different, all three companies demonstrated significant improvements, both in terms of safety and operational performance. The comparative analysis of the Tier 4 results for the three companies is shown in Table 7.9.

Table 7.9. Summary of results

Company	Compliance	Accidents (per year)	Absences (%)	Fines	Productivity
A (sea)	100%	30 → 24 (-20%)	5.2 → 3.9	0	+8%
B (average)	100%	-15% incident	4.8 → 3.9	0	+6%
C (small)	100%	6 → 0 (-100%)	6 → 2	0	+12%

Thus, level 4 fully confirms the strategic value of the digital platform: it is not just a training tool, but an organizational risk and performance management mechanism.

7.7.Conclusions

Through Kirkpatrick's analysis, it was demonstrated that technological intervention is not limited to making training more efficient, but generates systemic effects, measurable in the long term. The application of the Kirkpatrick model in the three companies demonstrates that the digitization of OSH training is transforming the way organizations understand, practice and measure safety. The platform is not just an IT tool, but a catalyst for cultural and organizational change, capable of producing real and lasting improvements.

Quantitative results – reduced accidents, increased productivity and compliance – are doubled by qualitative effects, such as increased employee trust, accountability and the emergence of a culture of continuous learning. Thus, the Kirkpatrick model applied in a digital context provides a valid and replicable framework for the evaluation of training in the field of road transport, confirming that the platform developed within the thesis meets the criteria of novelty, practical applicability and scientific value, contributing to the development of the concept of Safety 4.0 – an intelligent, integrated and sustainable approach to occupational safety and health.

Chapter 8. Contributions on the development and validation of a FRAM-Kirkpatrick hybrid framework for assessing the effectiveness of OSH digital training in complex socio-technical systems

8.1. Introduction

In order to demonstrate that the effectiveness of training in complex socio-technical systems cannot be significantly evaluated without a systemic perspective, the PhD student proposes the FRAM-Kirkpatrick Framework, which integrates the Functional Resonance Analysis Method (FRAM) with the Kirkpatrick training evaluation model.

8.2. Digital training in complex socio-technical systems

Within FRAM, each function is characterized by six fundamental aspects (*Inputs*, *Results*, *Preconditions*, *Resources*, *Control* and *Time*). Risks arise when the variability of several functions combine and amplify, generating negative functional resonance.

The Kirkpatrick model is one of the most widely used frameworks for evaluating the effectiveness of training, it consists of four levels: Level 1 (L1) - participant response, Level 2 (L2) - learning, Level 3 (L3) - behavioral change and Level 4 (L4) - organizational results.

8.3.Development of the FRAM-Kirkpatrick hybrid framework

The study adopts a mixed type design, combining FRAM functional analysis, quantitative evaluation of training using the Kirkpatrick model, and pre-intervention and post-intervention comparative analysis. The proposed framework is organized in an iterative cycle of evaluation and optimization, in which digital training, FRAM functional analysis and Kirkpatrick empirical evaluation are interconnected in a bidirectional relationship.

The functions of FRAM are identified through a complex analysis of operational processes, interviews with OSH experts, procedural documentation, observations of the actual activity (work performed). Examples of functions are: "Safe Driving", "Fatigue Management", "Compliance with OSH Procedures". Each function f is described by the set:

$$f = \{ I , O , P , R , C , T \} \quad (8.1)$$

where: i = *inputs*, o = *results*, p = *preconditions*, r = *resources*, c = *control*, t = *time*

The total variability V_f of a FRAM function is calculated as:

$$V_f = \sum_{i=1}^{n} wi\ \Delta Pi \quad (8.2)$$

where: ΔPi = the variation of the functional parameter i; wi = the weight of the functional parameter i.
This formula allows both the comparison before/after training and the analysis of the effect of training on functional stability. The integration of the two models is achieved by correlating the Kirkpatrick evaluation levels with the structural elements of a FRAM function. This mapping allows the association of training evaluation indicators with sources of functional variability (Table 8.1.)tag.

Table 8.1. Correlation of Kirkpatrick levels with FRAM components

Kirkpatrick Level	Evaluation objective	FRAM Component	Related indicators
Level 1 - Reaction	Acceptance of training	*Preconditions*	Satisfaction index, perceived usefulness
Level 2 - Learning	Acquiring knowledge	*Resources* / *Control*	Knowledge retention, test scores
Level 3 - Behavior	Transfer to practice	*Results*	Behavior change
Level 4 - Results	Systemic impact	*Functional resonance*	System Performance

By systematically correlating Kirkpatrick levels with FRAM components, the proposed framework allows quantifying the effect of training on functional variability. Kirkpatrick indicators become input variables for the recalculation of the variability of FRAM functions, and the observed changes can be expressed numerically by the total variability index V_f.

8.4. Case study - application of the FRAM–Kirkpatrick hybrid framework in road transport

8.4.1. Design of the quantitative analysis and working assumptions

In this study, instructional effectiveness was operationalized as a composite indicator derived from Kirkpatrick Levels 2 (Learning) and 3 (Behavior). [K02, B02] While Levels 2 and 3 reflect the direct effects of training on knowledge acquisition and behavioural change, Level 4 represents an organizational outcome influenced by several contextual factors. Consequently, Level 4 was used to validate the systemic impact of training through observed reductions in functional variability and safety events.

8.4.2. Description of the socio-technical system analysed

The quantitative analysis of the FRAM-Kirkpatrick Framework was carried out through a multiple case study applied in three road freight companies. The organizations were selected based on common criteria, including operating a fleet of more than 50 heavy-duty vehicles, carrying out long-distance international transport activities, implementing a digital training programme in the field of occupational safety and health, and the availability of safety-relevant operational data.

8.4.3. Description of the intervention: digital OSH training

For each company, a FRAM model of safe driving activity has been built, including functions such as: F1 - Trip planning; F2 - Driving the vehicle; F3 - Fatigue management; F4 - Compliance with OSH procedures; F5 - Reaction to unforeseen situations. Each function was described by the six FRAM aspects, and the variability of the parameters was estimated through telematic data, OSH reports, operational observations, expert opinion.

8.4.4. Evaluation of training — Kirkpatrick L2 and L3 data

Figure 8.1 and Table 8.2 summarize the mean pre- and post-training values, which were subsequently used as input variables in the quantitative analysis within FRAM-Kirkpatrick. The L2 assessment was carried out through standardized digital tests, integrated into the training platform used by the participating companies.

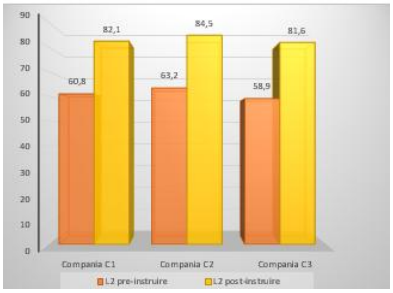


Fig. 8.1. Average values for pre- and post-training L2

The L3 assessment was based on objective operational indicators, extracted from telematics systems and internal occupational health and safety reports. Figure 8.2 and Table 8.3 show the pre- and post-training comparative values used in the subsequent quantitative analysis under the FRAM-Kirkpatrick Framework.

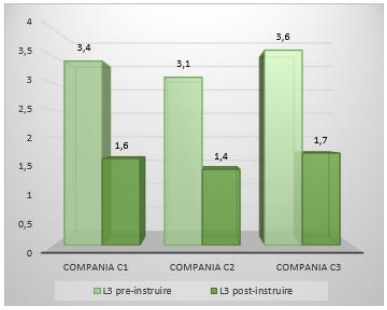


Fig. 8.2. Comparative values of pre- and post-training L3

8.4.5. Calculation of training efficiency

The effectiveness of the training was calculated by defining a composite Et indicator, which integrates the results of the Kirkpatrick L2 (Learning) and L3 (Behavior) levels, according to the relationship:

$$Et=0,5\cdot L2 + 0,5\cdot L3 \quad (8.5)$$

For L3 we turned the deviations into a positive score and chose the reference value for the maximum accepted threshold.

$$D_{max}=\max(D_{pre}\ ,\ D_{post}) \quad (8.8)$$

For the Kirkpatrick Level 3 (Behaviour) assessment, safety-relevant behavioural deviations were quantified as the average number of deviation events per driver per month, derived from telematics data and internal OSH reports. For this purpose, an empirical upper limit D_{max} was defined as the maximum value of the deviation observed in all companies and observation periods. The normalized behavioral score was then calculated as:

$$L3_{norm}=1 - \frac{D}{D_{max}} \quad (8.9)$$

ensuring that higher values correspond to safer behavioral performance.

Table 8.5 shows the aggregate values of training efficiency calculated for each participating company.

Table 8.5 Efficiency of training by company

Company	L2norm	L3norm	and
C1	0,821	0,556	**0,689**
C2	0,845	0,611	**0,728**
C3	0,816	0,528	**0,672**

The high value of the Et indicates that the training has produced both learning and significant behavioral change.

8.4.6. FRAM functional variability

Table 8.6 shows the values of the variations in the FRAM parameters for the pre- and post-training period, together with the weights associated with them. The comparison of the ΔPi^{pre} and $\Delta Pi^{post\ values}$ allowed the calculation of the aggregate functional variability, resulting in a reduction from Vf^{pre}=0.391 to Vf^{post}=0.215. The difference ΔVf=0.176 expresses a significant decrease in the undesirable variability of the analysed function, a value later used to correlate with the training efficiency indicators within the FRAM - Kirkpatrick Framework.

Table 8.6 FRAM variability (aggregate means)

FRAM parameters	Yes	ΔPipre	ΔPipost
Time	0,25	0,34	0,19
Resources	0,15	0,30	0,15
Control	0,25	0,46	0,23
Preconditions	0,20	0,38	0,26
Results	0,15	0,47	0,25

8.4.7. Correlation of training efficiency with system performance

The effectiveness of the training was expressed by the composite indicator Et, calculated on the basis of the Kirkpatrick L2 and L3 levels. The performance of the system was represented by the variation of the functional variability ΔVf, obtained from the FRAM analysis. To evaluate the relationship between these two variables, the Pearson correlation coefficient was calculated, defined by the relation:

$$r(E_t, \Delta V_f) = \frac{\sum(E_t - \bar{E}_t)(\Delta V_f - \overline{\Delta V}_f)}{\sqrt{\sum(E_t - \bar{E}_t)^2 \sum(\Delta V_f - \overline{\Delta V}_f)^2}} \quad (8.15)$$

The resulting coefficient, r(Et,ΔVf)=0.71, indicates a strong positive association between training efficiency and reduced functional variability, a value later used in the integrated analysis of the FRAM-Kirkpatrick framework.

8.4.8. Correlation of functional variability with organizational outcomes (L4)

In order to extend the analysis to the level of organizational results, the relationship between the reduction of functional variability ΔVf and changes in Kirkpatrick L4 result indicators was evaluated.

In this case, the Pearson correlation coefficient was also used, according to the relationship:

$$r(\Delta V_f, \Delta L4) = \frac{\sum(\Delta V_f - \overline{\Delta V}_f)(\Delta L_4 - \overline{\Delta L}_4)}{\sqrt{\sum(\Delta V_f - \overline{\Delta V}_f)^2 \sum(\Delta L_4 - \overline{\Delta L}_4)^2}} \quad (8.17)$$

The value obtained, r(ΔVf,ΔL4)=0.58, reflects a moderate association between the stabilization of functional performance and the improvement of organizational results. This correlation supports the use of FRAM functional variability as an intermediate variable between training effectiveness and system-level safety outcomes.

8.5. Results and discussions

The results of the FRAM analysis highlight a substantial reduction in the functional variability of the critical function analysed after the implementation of digital training. The aggregate value of functional variability decreased from V_f^{pre}=0.391 (in the pre-intervention period) at V_f^{post}=0.215 (in the post-intervention period), corresponding to a relative reduction of 45%. This decrease reflects the decrease in the amplitude of variations associated with FRAM parameters with a major impact on safety.

The results presented in Figure 8.3 highlight a clear and consistent reduction in the frequency of unsafe events per driver per month after the implementation of digital training for all three companies.

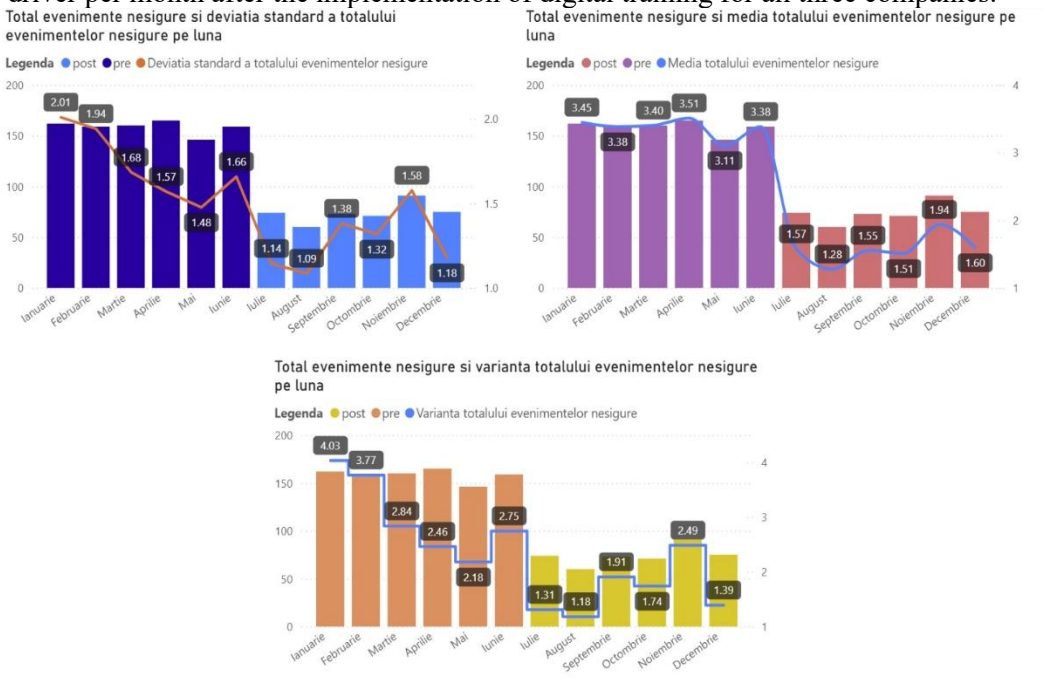


Fig.8.3. Distribution of unsafe events per driver per month before and after digital training

An important contribution is the empirical validation of the use of FRAM as a tool for evaluating interventions, not just as an explanatory method for accidents. By introducing quantitative indicators of variability and correlating them with the results of the training evaluation, the study demonstrates that FRAM can be used in a rigorous and clear manner to analyse the impact of organizational interventions, including digital training.

Chapter 9. Final conclusions and main contributions to the development of an integrated system for planning and optimizing operational processes and monitoring of work system components

9.1. Final conclusions

The main conclusions regarding the research and development activity carried out within the PhD, in order to fulfill the central objective, and correlated with the methodological benchmarks used, are presented below.

○ The development of an integrated planning and optimization system, correlated with the continuous monitoring of the components of the work system, has the potential to generate original contributions both at the theoretical level, by extending the existing models, and at the practical level, through direct applicability in industrial or service organizations.

○ OSH Online is an integrated web platform for managing Occupational Safety and Health, SU, PM and Human Resources activities. The system was created to provide a unitary and scalable solution, capable of meeting the requirements of organizations of any size, including those with a multi-site, multi-user and multi-lingual structure.

○ One of the most significant benefits of the integrated system for optimizing operational processes and monitoring of work system components is the elimination of dependence on physical documents and repetitive administrative work.

○ OSH training processes are, by their nature, exposed to a high level of functional variability. Modeling by FRAM allows the identification of critical nodes where variations can occur that, propagating in the system, affect organizational performance, legal compliance and worker safety (see § 6.1.5).

○ The FRAM analysis confirms that the proposed integrated digital platform is not just a technological solution, but a basic redesign of the OSH training process, which transforms a fragile and vulnerable system into a robust, adaptive and resilient system (see § 6.2.2).

○ The application of the Kirkpatrick model in the evaluation of the digital OSH training platform has demonstrated that digitalization is not just a change of form, but a fundamental transformation. The four levels of the model provided a complete perspective on the impact, from workers' perception to measurable organizational results, confirming the efficiency, scalability, and sustainability of the platform. (see § 7.4).

○ By integrating training assessment with functional system analysis, the FRAM-Kirkpatrick hybrid framework goes beyond classic linear approaches to training assessment. It enables empirical validation of FRAM interventions and provides decision-making support for the design of safety-oriented digital training (see § 8.7)

At a time when digital transformation is no longer an option, but an essential need, implementing a platform such as OSH Online is a natural step for any organization that wants to efficiently manage its activities in the field of occupational safety and health, emergency situations, RSVTI and Environment. Beyond technical functionalities, this platform changes the way internal processes are viewed and managed, bringing more clarity, order and control.

9.2. Personal contributions

In the process of achieving the central objective of doctoral research, the present thesis formulates several scientific contributions, the most significant of which are highlighted below.

- Design, development and validation of an integrated web platform for the management of OSH activities; the platform has as its main objective the digitization of compliance and operational management processes in the fields of HSM, SU, PM and HR, facilitating collaboration between all actors involved: employers, employees, internal specialists, external consultants and control authorities.
- OSH Online is a state-of-the-art digital ecosystem that combines OSH training, telematics, immersive learning, automated compliance, and real-time operational data.

- Digital signature integration is an important step towards modernization and compliance. The ability to sign documents directly in the platform greatly simplifies the process and eliminates the need for additional procedures.
- The reporting and monitoring component brings more transparency and managerial control. Dashboards and statistics provide a clear picture of progress, compliance, and any delays. Thus, management can have an overall perspective, and decisions can be based on concrete data, not just estimates.
- Secure electronic archiving provides peace of mind that documents are kept in secure conditions and can be consulted whenever needed. Backups and security measures protect sensitive information and help enforce data protection rules.
- Automating notifications and alerts for deadlines or non-compliances significantly reduces the risk of omissions. The system "reminds" users what to do, helping to maintain procedural discipline.
- The use of the FRAM method to highlight the vulnerabilities of the traditional OSH training process in the road transport industry, where trainings are carried out, in most cases, face-to-face, and the related documentation is kept exclusively on paper.
- A fundamental transformation brought about by the platform is the way of teaching. Instead of face-to-face sessions with variable attendance, workers benefit from online modules and VR simulations.
- Training planning no longer depends exclusively on the OSH manager, but is managed by a software engine that integrates legal requirements, employee profiles and training history.
- Realization of a FRAM comparative synthesis: traditional process vs. integrated digital process.
- Evaluation of the effectiveness of OSH training in three road transport companies using the integrated digital platform, using Donald Kirkpatrick's model, internationally recognized as one of the most widely used conceptual frameworks for the analysis of the effectiveness of training programs.
- To measure satisfaction in the three companies analysed, the digital platform used a standardized questionnaire applied at the end of each module. The questionnaire contained questions on a Likert scale (1 = "not at all satisfied", 5 = "very satisfied").
- The Kirkpatrick model applied in a digital context provides a valid and replicable framework for the evaluation of road transport training, confirming that the platform developed within the thesis meets the criteria of novelty, practical applicability and scientific value.
- The FRAM–Kirkpatrick Framework was developed and applied, a hybrid framework that integrates the Functional Resonance Analysis Method with the Kirkpatrick model of training evaluation.
- An important contribution is the empirical validation of the use of FRAM as a tool for evaluating interventions, by introducing quantitative indicators of variability and correlating them with the results of the training evaluation.
- By connecting training to the functional structure of real work, the proposed framework helps to go beyond solely compliance-oriented approaches and supports proactive and adaptive safety management.

* * *

This doctoral thesis, through its theme, the way it is treated and the conclusions obtained, creates its own conceptual framework that integrates operational performance, ergonomics and prevention of occupational risks in a unitary optimization system. OSH Online is proposed as an intelligent, cloud-native, and fully integrated platform designed to automate work processes, support real-time compliance monitoring, and provide full traceability of actions and responsibilities.

The scientific significance of the doctoral thesis is maintained at a high level by the innovative transformations brought to the efficiency and automation of the HSM, SU, RSVTI and HR processes, the reduction of the risk of accidents at work through rigorous planning, periodic checks and proactive monitoring, the increase of traceability, responsibility and transparency through a complete and adaptable digital platform.

The practical nature of this doctoral thesis lies in the fact that the proposed digital platform , OSH Online, can be adapted and implemented in various fields of activity, such as industry, services or public administration. Its impact lies in increasing the competitiveness of organizations and improving working conditions.

9.3. Perspective

In accordance with the principles of Industry 5.0, future research can deepen the human-centric dimension of the developed platform, by integrating adaptive customization mechanisms of the interface and information flows. Another research direction can be the integration of the OSH platform with ESG sustainability and performance indicators. Last but not least, a strategic research direction aims to analyse the resilience of the developed digital system in relation to major disruptions (health crises, logistical bottlenecks, legislative changes). Assessing the platform's ability to support operational continuity and quickly adapt internal processes to external changes is an essential element in the transition to intelligent and resilient organizations, according to the Industry 5.0 vision.

In conclusion, future research can extend the results of this thesis by integrating emerging technologies, deepening the human-centric dimension and developing predictive and multi-criteria models, contributing to the transformation of occupational safety and health systems in road transport into a strategic pillar of sustainable organizational performance.

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