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Digital Transformation of Manufacturing Processes in the Automotive Industry

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ABSTRACT

The digitalization of the automotive industry involves key factors such as customer experience, product innovation, strategy, organizational structure, process digitalization, collaborative work, IT infrastructure, culture, expertise, and transformation management. This article highlights five emerging trends reshaping the sector: connected vehicles, shared mobility and connectivity services, digital automobile sales, data analytics, and the rise of electrified vehicles. Our study outlines a six-step framework for digital transformation in the automotive industry. It begins with assessing a company's digital maturity, followed by creating an action plan, defining a digital strategy and objectives, developing a global roadmap, implementing changes, training teams, and launching a new operating model. A comprehensive model for the digital automotive industry is proposed, emphasizing the integration of technologies to digitize all processes. Key components include data management, connectivity, supply chain management, manufacturing execution, sales and marketing, customer relationship management, and analytics. The proposed model streamlines operations enhance performance, and improves customer satisfaction through tools like virtual control centers, AI, RFID technology, and online quality control. Additionally, a table summarizes the 12 core processes within the model. The article concludes with a practical tool for measuring digital maturity in the automotive sector, based on IATF 16949, VDA 6.3, and AIAG standards.

Keywords: automotive industry 4.0, process, digitalization, model, digital maturity, challenges

1. INTRODUCTION

Industry 4.0 originated as a strategic project of the German government to support the digital revolution of its industry. It is based on the ongoing digital revolution that we are currently experiencing. Industry 4.0 concerns all sectors of industry, the product life cycle, and especially their production. The most active players are ERP/EMS software publishers and equipment and automation providers. From a Lean point of view, Industry 4.0 offers interesting tools for automation and networking, but people remain at the heart of improvement processes (KAIZEN). We are only at the beginning of this revolution, which will accelerate with the development of AI. We must be wary of over-inversion, and implementation should be done gradually, in a modular and flexible manner.

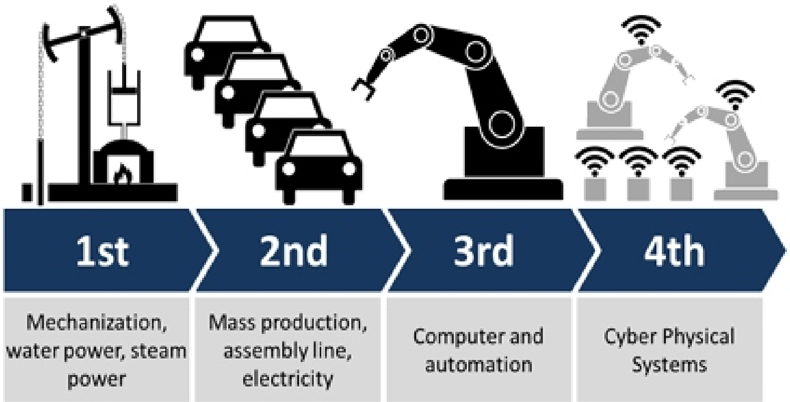

Figure 1. the evolution of industry 1.0 to 4.0

2. Digital maturity in the automotive industry

The advancement of a company in digital matters is measured by taking into account its technological knowledge combined with its motivation to enrich and deploy this know-how. Digital maturity questionnaires proposed by consulting experts generally focus on the following aspects:

• Customer experience: The company has implemented the ability to interact with the customer in order to collect useful data for adjusting marketing and communication strategies.
• Product innovation: The company has adapted its products and services to digital innovations.
• Strategy: The company prioritizes the development of digital projects and can clearly define the skills it needs to ensure the success of the company.
• Organization: The resources available are sufficient and the company is flexible enough to quickly respond to technological developments.
• Digitalization of processes: The company has integrated digital channels for communication, processes, and services.
• Collaborative work: Employee collaboration is done through digital platforms and internal experts are responsible for managing digital-related issues.
• Information technology: The internal IT department is capable of quickly integrating new products and services.
• Culture and expertise: Digital expertise occupies a central place in the development of the company, and employees master digital products.
• Transformation management: Digital transformation follows a strategic plan and clearly defined objectives.

3. Five New Trends to Reshape the Automotive Sector in The Coming Year.

3.1. Penetration Of Connected Cars

Connected cars equipped with the Internet of Things (IoT) technology offer enhanced safety and comfort to passengers. This technology enables a convenient multimedia experience with ondemand features that enable drivers to access web-based services while operating their vehicles. Connected vehicles have the ability to communicate in both directions with a range of external systems and can share internet connectivity and data devices both inside and outside the car. These cars can share information and monitor services such as remote diagnostics and digital data, vehicle health reports, access to 4G LTE Wi-Fi hotspots, data-only telematics, turn-by-turn directions, and provide information on car health issues that allow users to take preventative measures and avoid breakdowns.

3.2 Shared Mobility, Connectivity Services, And Feature Upgrades

There is a significant shift underway in individual mobility behavior, driven by changing consumer preferences, stricter regulations, and advancements in technology. This shift is expected to result in a substantial increase and diversification of the automotive revenue pool, with a significant portion being derived from data-driven services and on-demand mobility solutions. This shift has the potential to generate up to $1.5 trillion in additional revenue by 2030, which represents a 30% increase from traditional car sales and aftermarket services/products. This is a significant increase from approximately $3.5 trillion in revenue generated in 2015, which is projected to rise to around $5.2 trillion by 2030.

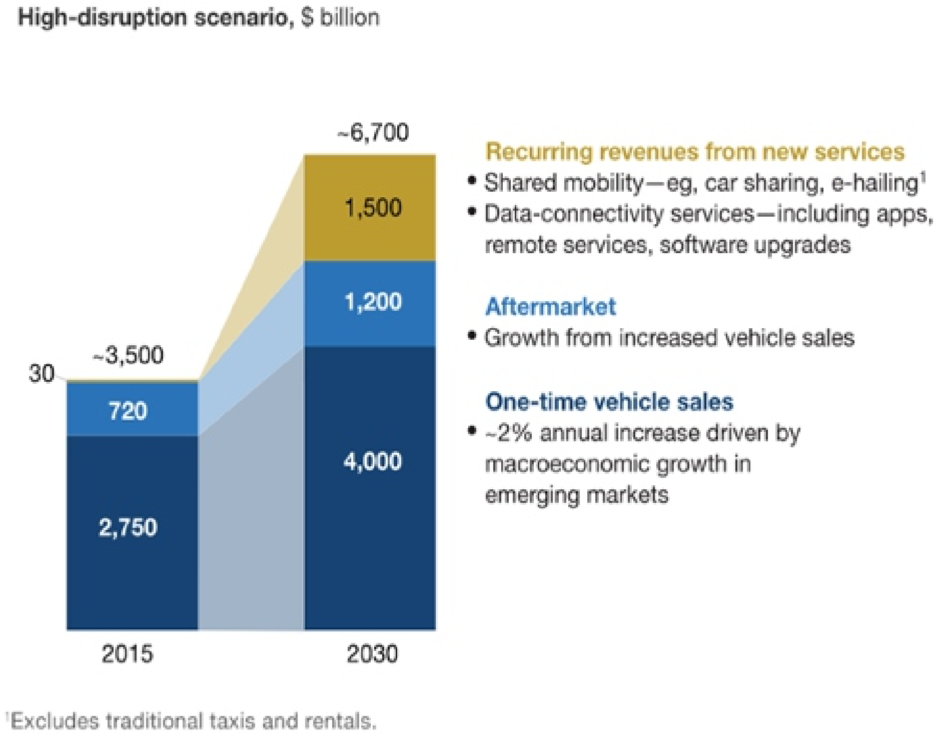

Figure 2. the turnover evolution till 2030 (Source: McKinsey & Company)

Connectivity, and later autonomous tech, will increasingly provide the car to become a platform for passengers and drivers to utilize their time in transit to devour novel services and media or dedicate the freed-up time to other personal activities. The accelerating speed of advancements,
especially in software-based systems, will need cars to be upgradable. As shared mobility services with short life cycles will become more common, customers will be constantly aware of technological advancements, increasing demand for upgradability in privately used cars.

3.3. Digital Automobile Sales

Automotive companies are considering various ways to simplify the vehicle buying process for consumers by exploring the idea of virtual showrooms, making it possible to purchase cars online. The demand for virtual showrooms has surged due to the COVID-19 pandemic, which restricted physical movement. Even after the pandemic, consumers still prefer online shopping for cars, and automobile companies find virtual showrooms advantageous as they facilitate sales, reduce overhead and infrastructure costs, and enable retailers to offer attractive deals and competitive prices. In addition, online purchasing provides other benefits such as virtual car tours, online documentation, and secure payment options.

3.4. Leveraging Data Analytics

Data analytics provides a promising prospect for car dealerships that are eager to leverage technology to differentiate themselves from their rivals. By employing automotive retail analytics, dealerships can track customer movements within their showrooms. Additionally, analytics and behavior-sensing technology facilitate the creation of heat maps, as well as the installation of digital signage or cameras in high-traffic areas. By pairing these features with interactive displays, dealerships can tailor their marketing messages to appeal to millennial customers and cater to their preferences. By utilizing behavior prediction technology, auto retail sales teams can enhance their effectiveness and provide the necessary resources and messaging to enable dealers to stay ahead of the industry curve.

3.5. Electrified Vehicles

Stricter emission regulations, widely available charging infrastructure, lower battery costs, and increasing consumer acceptance will create new and robust momentum for the penetration of electrified vehicles (plug-in, hybrid, fuel cell, and battery electric) in the coming times. The pace of adoption will be determined by the interaction of customer pull (partially driven by the total expense of ownership) and regulatory push, which will vary enormously at regional and local levels. By 2030, the share of electrified vehicles could go up from 10% to 50% of new-vehicle sales. Adoption rates will be on top in densely developed cities with strict emission regulations and consumer incentives (special parking, tax breaks, driving privileges, discounted electricity pricing, and more). Sales penetration will be slow in rural areas and small towns with higher dependency on the driving range and low levels of charging infrastructure. Through continuous improvements in battery technology and expense, the local differences will become less pronounced, and electric vehicles are expected to gain more market share from standard vehicles. With battery prices potentially decreasing to $150 to $200 per KW-hour over the next 10 years, electrified vehicles will achieve price competitiveness with traditional vehicles, creating the most crucial catalyst for market penetration. In the same manner, it is significant to note that electric vehicles involve a large portion of hybrid electrics, which means even beyond 2030, the internal-combustion engine will remain very pertinent.

4. Automotive Industry 4.0 challenges

Today, the automotive industry witnessed a massive transformation. The transformation is pervasive across the automotive manufacturing value chain and much of it is driven by the potential of industry 4.0. At the wake of leveraging the potentials and benefits of industry 4.0, automotive company stakeholders and executives are bound to face challenges.

- One of the biggest challenges is to have the right skilled people in place to effectively plan, execute, measure and optimize technologies and digital systems.

• Another challenge is to opt for a suitable approach. The transformation is viable provided the whole organization is aligned with a specific digital strategy rather than an individual isolated strategy for each department. In other words, a holistic approach to digital transformation in the automotive industry witnesses greater success as opposed to an isolated approach.
• Another approach that has been adopted by auto manufacturers in the process of digital transformation is by starting to solve small problems. When small challenges are resolved right, it sets precedence for stakeholders, executives and technical expertise to delve into implementing industry 4.0 on the same page whilst focusing on the core value propositions of the company.
• Specific to the automotive industry, supply chain integration can seem challenging initiating a transformation to industry 4.0. Auto manufacturers rely on external partners and contractors for supplies and logistics which often becomes a challenge in integrating all stakeholders into one ecosystem. Initially, the process might seem daunting, but eventually with the right choice and use of industry 4.0 technologies, smart factories can be achieved.
• Vulnerable to cybersecurity threats with industry 4.0 in automotive manufacturing is another challenge. In order to eradicate this threat, stringent mechanisms and policies are to be put in place to ensure data security.

1. The connectivity of software and equipment, including existing equipment.
2. The standardization of norms and processes that facilitate data sharing.
3. The reengineering of work methods and processes.
4. The management of cybersecurity in order to protect sensitive information and know-how.
5. Access to digital technology specialists.
6. The development of new skills.

5. The six steps of digitalization in automotive industry:

This digital transformation is fundamentally characterized by automation and by integrating new technologies into the company's value chain. The exploitation and massive management of data, the interconnection of machines, the dematerialization of communication and distribution channels and restructuring of the company for a flexible and personalized production, in order to succeed we propose here an action plan with six main steps:
1. The company must take the first step towards digitalization: analyzing its level of digital maturity (like an audit).
2. The result of this analysis, audit or assessment should lead to an action plan that the company must follow to outline its digital strategy.
3. Once these elements are gathered, the company can define a digital strategy and the objectives of its digital transition.
4. These goals serve the company, in a fourth step, to create a global roadmap, parallel to the implementation of changes aimed at starting the digital transition.
5. After that, the company must focus on how these changes will be managed within the team of collaborators.
6. The final step is the launch of the new operating model.

6. Fist model of automotive Digital industry:

Digitizing the Automotive Industry, the majority of manufacturers currently working in the specialized automotive industry follow processes that are all customer-oriented, whether it's internal customers (process-to-process relationships) or external customers (relationships with partners). As we will see later on, these manufacturers are all IATF 16949 certified without exception. The most common model is as follows

6.1 digitalize all processes of the automotive industry

To digitalize all processes of the automotive industry, you will need a core model that encompasses several key elements, including:

1. Data management: A robust data management system that can store, process, and analyze vast amounts of data from multiple sources, such as production data, sales data, and customer data.
2. Connectivity: A system that can connect different parts of the automotive industry, such as suppliers, manufacturers, distributors, and dealers, to facilitate the flow of information and goods.
3. Supply chain management: A system that can optimize the flow of materials and products through the supply chain, from procurement to delivery, and track the status of orders, shipments, and inventory.
4. Manufacturing execution: A system that can manage the production process, from the scheduling of production runs to the tracking of production performance and quality control.
5. Sales and marketing: A system that can support the sales process, from lead generation to customer service, and track the performance of marketing campaigns and the customer experience.
6. Customer relationship management: A system that can manage interactions with customers, from lead generation to post-sale support, and track customer preferences, behavior, and satisfaction.
7. Analytics and reporting: A system that can analyze and report on key performance indicators (KPIs), such as sales, production efficiency, and customer satisfaction, to help organizations make informed decisions.

6.2 Total digital Management using industrial KPIs

This core model will provide the foundation for digitalizing all processes of the automotive industry, enabling organizations to streamline their operations, improve their performance, and enhance them.

- The flow throughout the supply chain (and the supply chains of suppliers and subcontractors) are planned via the internet (portal) to satisfy these customers in Quality, Cost and Delay.
- Each order placed triggers the production order of the vehicle (or component in case of supply from the supplier Tier1 and Tier2
- The simulation made at the control center (calculation of the total supplay chain) will notify the customer by the date and place of delivery of his vehicle (component in case of supplier Tier 1 or Tier 2)
- Control centers are virtual platforms (AI) that simulate scheduling the various tasks of production, material supply to satisfy the customer order before sending a confirmation to the customer.
- The routing of parts is fully automated thanks to robot operators and perfectly fluid and flexible RFID technology.
- Workspaces are cleared, heavy tasks are programmed via robots, otherwise witnesses (laser sensors) managed by programmable logic controllers.
- Quality control is carried out online, the values entered on the system make it possible to validate or block the product is validated by the operator.
- It is in the production control center that decisions are made and correction to any drifts are taken in real time, thanks to ultra-connected processes technology Quality controls are done automatically on the ERP, or even in case of parts received from a supplier

• At the design level, the evolution of models is optimized by the visualization of 3D models on production lines.
The 12 processes known and used in any company operating in the automotive industry are grouped in the following table:

Table 1. the 12 processes known and used in the automotive industry

Process	Target TDM (Total Digital Management)	Mean digital KPI
1. maagement processes		
2. purchasing processes		QCD: Quality, Cost, Delay
3. Supply chain & logistique management proceess	Coordination of the flow of materials, components, and finished goods between suppliers, manufacturers, and customers Movement of finished vehicles and components from the manufacturing plant to dealerships and other final destinations	OTIF, Lead time, delivery accuracy, inventory levels, supplier performance Delivery speed, delivery accuracy, transportation costs, customer satisfaction
4. Research and developement process	Development of new automotive products and components using advanced technologies such as 3D printing, computer-aided design (CAD), and virtual reality (VR)	Time-to-market, design accuracy, number of product recalls, customer satisfaction
5. Human research process		
6. Continus improuvement process		

7. Manufacturing process	Automated assembly and production of automotive components and vehicles using robotics and other advanced technologies	Production speed, product quality, inventory levels, machine utilization, TRS, Scrap Rate
8. Maintenance process		MTBF ; MTTR ;
9. Finance process		EBITDA
10. Sales & marketing process		Turnover
11. After sales service precess	Provision of maintenance, repair, and other services to customers after the sale of a vehicle	Repair time, customer satisfaction, repeat service visits, warranty costs
12. Information technology process		

Table 2. The level of digital maturity according to the digital tools

Level of digital maturity	**Recearch & developement process**	**Adminitrative & Information technology process**	**Supply chain & logistics management process**	**Manufacturing process**	**Services**
8	FAO Advanced	Big Data			Intégration
7	CAO 3D Paramétrique	Commerce Electronique	RFID		IOT
6	PDM -PLM	Configurateur of product		Additive manufacturing	Prédictive maintenance
5		Business Intelligence		Cobotique	Cybersécurité
4		GED	APS	FMS	Mobility
3	CAO 3D	WMS	MES	Robotique	Connectivity
2	FAO	CRM	Barre code	PLC	Maintenance préventive
1	CAO 2D	ERP	ERP	CNC	Networking

Table 3. Automotive industry and Lean manufacturing

IATF	Industrie 4.0	Lean Manufacturing
Customer focus	Autonomie	Value
Leadership	Inter opérabilité	The value chain
Engagement of people	Durabilité	The Flow
Process approach		Traction
Improvement	Cyber Phyisical Security	Perfection
Evidence-based decision making	IOT/IOS	Elimination of waste:
Relationship management	Big Data	1- Overproduction
	Self maintenance	2- Overstock
Customer and stakeholder specific requirements (CSR)	Autonomous collaborative robots	3- Waiting time
PDCA	3d printing	4- Moving unuseful
DFMEA & PFMEA	Clourd computing	5- Unnecessary transport
APQP	Simulations	6- Defects
SPC & MSA		7- steps without VA
APAP		
Reduction of variability and losses in overall SC		

6.4 Future perspectives of the IATF 16949

IATF 16949 is an international standard for quality management systems in the automotive industry. It was developed by the International Automotive Task Force (IATF) and is based on the ISO 9001 standard. The standard specifies requirements for a quality management system that organizations in the automotive industry can use to ensure that their products and services meet customer and regulatory requirements.

The IATF 16949 standard is currently in its 2016 version, but a new version is expected to be released in 2023. This new version is expected to have a greater focus on sustainability and the use of new technologies, such as electric and hybrid vehicles, as well as connected and autonomous vehicles.

In terms of the future perspective, it's important to note that the automotive industry is constantly evolving and there are many factors that can affect the adoption and implementation of standards like IATF 16949. For example, the increasing focus on electric and autonomous vehicles, as well as the rise of connected and shared mobility solutions, may lead to changes in the way quality management systems are approached in the industry.

One area where the new IATF 16949 standard may have an impact is in the production of batteries for electric and hybrid vehicles. The standard is expected to specify requirements for the design, development, and production of these batteries to ensure that they meet safety and performance standards.

The CAN (Controller Area Network) protocol is a widely used communication protocol in the automotive industry. It is used to allow different electronic systems in a vehicle to communicate with each other. The new IATF 16949 standard is expected to specify requirements for the use of the CAN protocol in the design and development of automotive systems, including requirements for the testing and validation of these systems.

In summary, the new IATF 16949 standard is expected to have a strong focus on sustainability and the use of new technologies in the automotive industry, with implications for the production of batteries for electric and hybrid vehicles, as well as the use of the CAN protocol in automotive systems.

7. How to measure digital maturity in the automotive industry?

We must answer a questionnaire according to our status at the time of the audit. To calculate the maturity level of each item, we need to multiply the three key factors: technology, mastery, and integration of this technology within the process. The result is a radar graph. Each axis should be placed in one of the five levels of digital maturity obtained.

Table 4. Maturity level rating

1	Traditionalist	It's time to set foot in digital transformation
2	Aspirant	Very good start
3	Evolutionary	Bravo, we must continue on this beautiful momentum
4	Modernist	Open to change, still some small efforts
5	Futuristic	The ultimate level: has developed remarkable digital ingenuity

Table 5. Seven Chapters to assess the maturity of the company

CHAPTER 1	**STRATEGY & IMPROVEMENT**	Note /10
	• Vision & Strategy	
	• Objectives	
	• Measurement, Analysis and Action Plans	
	• Continuous improvement	
	• Supply Chain Development	
CHAPTER 2	**WORK ORGANIZATION**	
	• Organizational processes	
	• Organizational processes	
	• Resource planning	
	• Factory Environment and Human Resources	
CHAPTER 3	**PRODUCTION CAPACITY & PLANNING**	
	• Product Development	
	• Capacity planning	
	• Production planning	
	• Systems Integration	
	• Production operations	

CHAPTER 4	**COSTUMER INTERFACE**	
	• Communication	
	• Packaging & Labelling	
	• Shipping	
	• Transport	
	• Customer satisfaction & Feedback	
CHAPTER 5	**PRODUCT / PROCESS MASTERY**	
	• Product identification	
	• Inventory management	
	• Change management	
	• Traceability	
CHAPTER 6	**SUPPLIER INTERFACE**	
	• Selection of suppliers	
	• Logistics Protocol	
	• Communication	
	• Packaging and labelling	
	• Transport	
	• Reception	
	• Performance measurement	
CHAPTER 7	**MAINTENACE**	
	• preventive maintenance	
	• predictive maintenance	
	• self maintenance	
	• MMAO	

Table 6. Example of questionnaire audit « digital level » :

	Item	**Technology**	**mastery**	**Intégration**	**Level of digital maturity = somme (technology x mastery x intégration).**
1. 4. 25	Are the complete physical inventories PF, MP and WIP PR automated: using technologies that allow easy access to data such as RFID readers, barcodes, etc.	3	2	3	12
4. 1. 22	Delivery requests (DELJIT, shipping forecasts, synchronous shipments) from customers must be received electronically and integrated without human intervention.	3	3	3	27
1. 2. 26	The available tools make it easy to calculate the Costs of Non-Quality	1	2	3	6

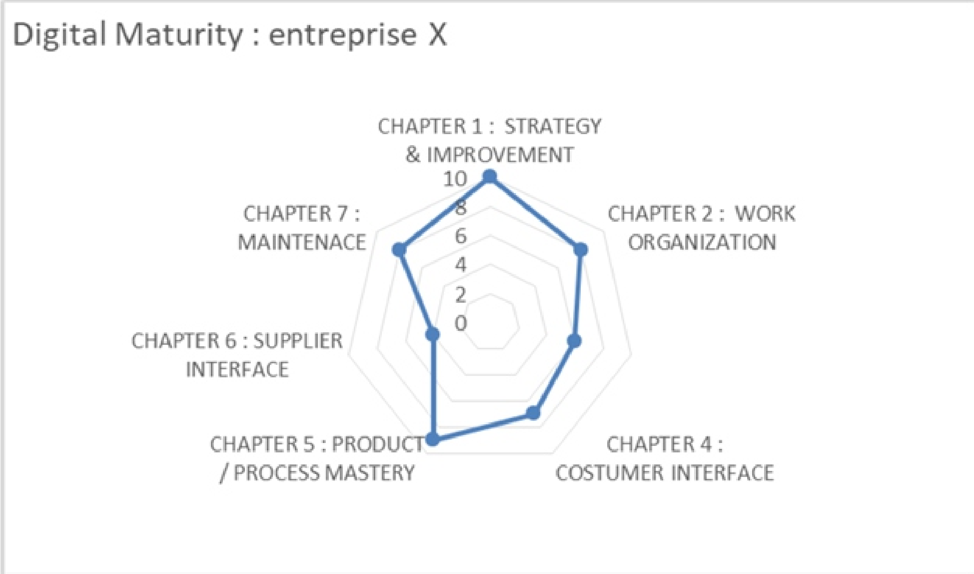

Figure 3. Radar graph of the seven-axis maturity level

Use case studies or examples from the automotive sector to illustrate maturity levels. For instance:
- A company at Level 3 might implement digital twins to simulate production processes.
- A Level 5 company might employ real-time adaptive manufacturing using AI and IoT.

8. literature review 2019-2024

The digital transformation of manufacturing processes in the automotive industry has been a focal point of research between 2019 and 2024. Key themes include the integration of advanced technologies, the development of digital capabilities, and the shift towards sustainable practices.

8.1 Integration of Advanced Technologies

The adoption of technologies such as 3D printing, advanced robotics, and the Industrial Internet of Things (IIoT); Wikipedia
Development of Digital Capabilities; ResearchGate
Transition to Sustainable Practices; ResearchGate & IEEE Xplore

8.2 In summary, the period from 2019 to 2024 has witnessed substantial advancements in the digital transformation of automotive manufacturing processes. The integration of advanced technologies, development of digital capabilities, and commitment to sustainable practices have collectively contributed to the industry's evolution.

Recent Developments in Automotive Digital Transformation
The Auto sector scrambles to retool workforce for electric and automated future; Reuters

Toyota and Volkswagen fall further behind in the software race; Financial Times

Conclusion

The automotive industry is rapidly transitioning toward Industry 4.0, marked by the adoption of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and machine learning. These innovations enable highly automated, data-driven, and interconnected manufacturing processes, leading to significant gains in efficiency, flexibility, and production speed.

Achieving digital transformation in the automotive sector requires assessing and advancing a company's maturity level. This maturity is evaluated based on several critical criteria, including technology infrastructure, business processes, workforce competencies, performance measurement, and strategic alignment. Organizations progress through maturity levels, starting with isolated digital initiatives and advancing toward fully integrated, self-optimizing smart factories characterized by Industry 4.0.

The first proposed model for the automotive Industry 4.0 emphasizes the integration of these criteria and outlines key performance indicators (KPIs) for evaluating the success of each process. By adopting this model, organizations can streamline operations, enhance productivity, and improve customer satisfaction. Simulating and implementing the digital automotive model, however, is a complex endeavor involving well-defined steps, which will be detailed in our next publication.

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The Training Program: "Student-centred and Gamified Learning. Exploiting Dilemma – Dibl"

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ABSTRACT

Within the framework of the Erasmus+ program "Gamified Introduction to Gamification", (2021-2-EL01-KA210-SCH-000050330), a series of twelve (12) training actions were carried out. These actions were implemented in three parallel cycles, each lasting one week, during the period from February 20 to March 17, 2023 in various areas of the Peloponnese Region. The purpose of this presentation is to present the theoretical background, material and procedures of the training. The objective of the training activities, as formulated by the trainers of the program, was to familiarize themselves with and utilize the principles of student-centered learning and gamification, as well as the utilization of dilemma, through the dibl platform, in the educational process. The deliverables, on behalf of the trainees, were the design, implementation and evaluation of educational scenarios in which the above learning processes were integrated, depending on the specialty and the subject of teaching of each participant.

Keywords: Learner-centered learning, gamification, dilemma

1. INTRODUCTION

On May 30, 2022, took place the official launch of the Small Scale Partnership entitled: GIG Gamificated Introduction to Gamification (2021-2-EL01-KA210-SCH-000050330), within the framework of the implementation of the Erasmus+ KA210 project. The planned duration of the partnership extended until May 29, 2024. This partnership consisted of 29 participants - partners (schools and Directorates of Education of the Peloponnese Region with the assistance of two partners from the European Union) among which is the General Lyceum of Molaoni "Thodoris Kallifatidis", a school of service, at that time, of the writer. The partnership's goal was threefold: familiarization with student-centered teaching methods, creative use of the game, and application of the principles of dilemma-based learning through the digital application dibl within the context of each subject. To implement the partnership's goal, two cycles of training activities were carried out: a weekly training of twelve trainers in November 2022 under the supervision and guidance of the "Europass Teachers Academy" organization and a series of twelve corresponding weekly trainings in February - March 2023 under the responsibility of the twelve individuals who were trained in November 2022. The title of the training seminars of the second cycle was "Student-centered and gamified learning. Utilization of the Dilemma - dibl".

2. Clarification of concepts – theoretical background

2.1 Student-centered learning

In place of the current, adult-centered, hierarchical structure where students are the recipients of a predetermined set of knowledge, a proposal has been submitted to redesign the school education model with students at the center. Student-Centered Learning, as an educational process, takes into account students' interests, learning styles, cultural identities, life experiences and personal challenges (Kaput & Education Evolving, 2018). Its main concern, beyond the achievement of various types of goals (cognitive, emotional, attitudinal, skills) is to respond to the unique needs of students.

A multitude of research efforts through empirical studies and meta-analyses have documented the benefits for students from the use of student-centered teaching methods at the level of Primary, Secondary and Tertiary education students. Lee & Branch (2018), highlighted, in the context of student-centered learning, the importance of students' prior knowledge as well as its role in achieving learning objectives. Agustini et al. (2021), argued that the implementation of the stages of student-centered learning models provides constructive learning elements: activation of existing knowledge, acquisition of new knowledge, understanding of knowledge (through hypothesis formulation, exchange, revision and development of concepts), practice of knowledge and skills (application of knowledge). Finally, Bechter et al. (2019), believe that their research findings demonstrated that the use of learner-centered teaching strategies has the potential to motivate the student and strengthen mechanisms for pursuing positive outcomes (e.g., increased need satisfaction).

Integrating active learner-centered learning strategies during lessons can be a challenge. Several studies have described different strategies, including those that are easy to implement, that can be used to create a more student-centered approach in learning classroom (Allen, & Tanner, 2005 · Michael, 2006 · Tanner, 2013). Specifically, simple strategies that can be used with minimal preparation and still lead to meaningful "student-centered" classrooms include encouraging all students to write down their answers to a question that is posed, keeping records, Think – Pair – Share activities, using personal response systems, creating another version of the story. In addition, students can be asked to watch videos or read specific material before teaching (flipped classroom) and then engage in various activities that utilize the information, either individually or in groups (e.g., assessment quizzes). A simple suggestion that allows for the creation of an active student-centered classroom, and indeed with a minimal amount of additional work, is to present to students a problem – a topic at the beginning of the lesson that they would normally have to answer once the teaching is over. In this way, the teacher's usual lecture could serve as feedback for students and allow the construction of personal mental models and representations of the material, thus maximizing learning (Posner et al., 1982).

2.2 Gamicification

Gamification in the context of learning has received increased attention and interest in recent years for the promised benefits, by its proponents, for student motivation and learning in general. Gamification is related to the use of game design elements in non-game environments (Deterding et al., 2011). The term "games" or "serious games" refers to a system, digital or non-digital, in which players engage in an artificial conflict, defined by rules, that leads to a quantifiable outcome (Salen & Zimmerman, 2004). Gamified learning approaches do not design games nor are they used to replace an educational process, but focus on modifying an already existing learning process, in a real environment, with the aim of creating a revised version of this process that users experience as a game (Landers, 2014 · Landers et al., 2018). Based on the above conceptualization, Hamari et al. (2014), distinguish that gamification consists of three main parts: the implemented motivational activities, the resulting psychological effects and further behavioral effects. At the same time, Landers (2014) in his paper lists four components (educational content, behaviors and attitudes, game characteristics and learning outcomes), suggesting that educational content directly affects learning outcomes and student behavior.

In this context, and based on the findings of the recent review by Zeybek & Saygı (2023), it is possible to argue that gamification is used for various educational purposes, at many levels of learning, in various environments and in a wide variety of learning fields. Based on behavioral assumptions, gamification utilizes stimuli and external rewards and directly affects the extrinsic motivation of learners (Zuckerman & Gal-Oz, 2014). Leaderboards, points, rankings, competitions, and leveling are the most common game elements depending on the learning area, and are regularly used for gamification in order to cultivate a creative, competitive environment. (Hamari et al., 2014 · Kalogiannakis et al., 2021).

Modern research, despite a few objections (e.g. Klabbers, 2018 · Toda et al., 2017), seems to have accepted the benefits of implementing gamified learning processes. Thus, according to Chow et al. (2011), through gamification, students can learn in an exciting and fun way while increasing their understanding of the subject. At the same time, Krath et al. (2021), argue that gamification has the potential to clearly illustrate goals, push learners through guided pathways, provide immediate feedback, enhance good performance, and simplify content into smaller, more manageable goals. In an analysis of 32 qualitative studies with student subjects Bai et al. (2020), reveal that students enjoy gamification because it enhances enthusiasm, provides feedback on performance, satisfies their needs for recognition, and promotes goal setting. Thus, it seems well documented both the overall positive contribution of Gamification and its ability to adequately manage educational problems (Zeybek & Saygı, 2023).

2.3 Dilemma-based learning

Dilemma-Based Learning (DBL), based on Kohlberg's (1969) theory of moral development, began as a method of thinking that focuses on the use of dilemmas to improve an individual's moral reasoning ability (Wood et al., 2007). A dilemma, whether moral or not, can be defined as an internal dialogue about a confusion between two propositions in a situation (ShapiraLishchinsky, 2010). These two propositions contain unpleasant outcomes, often equivalent, but also a valid argument from two equivalent options (Harding, 1985). Therefore, the seriousness of the issues under consideration is determined by subjective factors of the individual facing the conflict.

Dilemma-based learning, as an educational approach, focuses on utilizing dilemmas to improve students' reasoning skills. In the classroom, dilemmas are used to facilitate group discussions and help students make logical decisions. Of paramount importance is the assumption that dilemmas can have multiple solutions (Caruana, 2021). Exploring the limits of autonomous rational thinking, cultivating mature decision-making and problem-solving skills are the primary goals of dilemmas. Moreover, problems that are applied to real-world situations, promoting cognitive stimulation and enriching learning experiences. Dilemma-based learning combines pedagogical concepts such as cooperative learning, the ethic of care, and self-regulation. According to Settelmaier (2003), dilemma stories can be presented in various formats, including role-playing, a summary of problematic situations, films and storytelling.

Dilemma-based learning has gradually been integrated, beyond Ethics lessons, into other teaching subjects such as Religious Studies, History, Languages and Personal, Social and Career Development (Wood et al., 2007). A typical example is the subject of Chemistry, in which topics such as salt hydrolysis, organic chemistry, environmental chemistry, carbonic acid in soft drinks, detergents, preservatives and seawater have been approached through dilemmas (for an rerview see Winarti et al., 2021). Going a step further, Rahmawati et al. (2022), argued that the use of dilemmas in the subject of Chemistry can empower secondary school students not only in their deep knowledge of the subject, but also in the cultivation of interdisciplinary skills for solving local environmental problems.

2.4 The dibl digital application

The dibl digital application has been developed by Serious Games Interactive, a software company based in Denmark. It is one of the partners of the Erasmus+ partnership, which is responsible for the design, configuration and ensuring the smooth operation of the Dibl platform. Currently, this application is not available to the general public and is used exclusively by the trainers and trainees of the partnership's training actions to support the design and implementation of teaching scenarios based on the dilemma, within the framework of this specific program.

2.5 The role of the teacher

The above-mentioned educational approaches create the need for modification - differentiation of the teacher's role compared to the one that was established, at least, until relatively recently. Thus, teachers need to examine the needs of students, as a group and as individuals, and encourage them to actively participate in the learning process (Emaliana, 2017). A new, studentcentered - facilitating, role is reserved for the teacher. Teachers now function, according to Donnelly & Fitzmaurice (2005), as subject advisors for students, coordinating resources and facilitating the learning process. Their focus is not simply on solving problems but, above all, on developing critical and creative thinking skills. Teachers should, with probing questions, create an open learning environment in which students are encouraged to provide creative and adequately reasoned solutions. Group discussions and respect for different perspectives are effective ways to explore different opinions and solutions (Caruana, 2021). A key concern, according to Flores-Aguilar et al. (2023), is the mobilization of learners.

3. Seminar series: “student-centered and gamified learning. Exploitation of dilemma – dibl»

3.1 Implementation

From February 20 to March 17, 2023, three cycles of twelve training programs, each lasting one week, were held in various areas of the Peloponnese region, under the title "Student-centered and gamified learning. Utilization of dilemma - dibl". As can be deduced from the title of the seminars, their goal was threefold: familiarizing participating teachers with the principles of student-centered learning and gamification, while introducing them to dilemma-based learning and the utilization of the dibl platform. These goals were achieved through activities of both a digital and non-digital nature. Practical application of the above knowledge and deliverable material by the participants was the design, implementation and evaluation of teaching scenarios related to subjects and thematic units of their specialty.

To achieve the program's goals, a series of modern educational methods were utilized. The main concern of the trainers was the cooperation of each department's members at the individual group level and at the plenary level. In order to do so both modern training and utilization of collaborative tools for distance learning (e.g. Padlet) xere used. The activities were governed by experientiality and an effort was made to document the experiences of the participants, in accordance with the principles of adult education. This was necessary given that what was required for them was a change in the way of approaching teaching subjects and the support of more student-centered and gamified teaching scenarios. On a daily basis, there were relaxation and de-stressing activities, dialogue activities and opportunities for expression through targeted and appropriate mobilization, as well as activities to evaluate the daily program. The use of extensive presentations and lectures was avoided and limited only to the clarification of necessary concepts and theoretical material.

The planning, implementing and evaluating the training program was the responsibility of the twelve trainers under the coordination and guidance of Mr. Kelefiotis, member of PEKES Peloponnese and coordinator of the Erasmus+ program. The structure and content of the seminar was guided by the corresponding training action in English by the Europass Teachers Academy in November 2022. The cooperation of the seminar leaders resulted in the necessary modifications and the development of the daily program of the seminar on a single basis and under a common, in principle, program. The seminar lasted thirty (30) hours and was held daily,

between 09:00 a.m. and 2:00 p.m. Due to the strong presence of the digital element, as will be presented in detail below, there was a need to utilize computer labs in order to have the appropriate logistical infrastructure. The structure of the program, which follows, and without differing particularly from the other programs, is related to the educational seminar that was implemented at the Molaion High School "Thodoris Kallifatidis", in Molaioi, Laconia, during the period 20-24 February 2023.

During the first day and after the arrival of the trainees, two activities to get to know each other and "breaking the ice" were held. The first concerned the self-presentation of each member of the group. The second was the "Human Bingo" activity. The participants had a card with various personality traits in their hands and had to look for the person or people who met these criteria and present them to the plenary. Then, the fears, capabilities and expectations of the trainees from their participation in the seminar were recorded in a playful way. Information was provided about the collaborative space for posting educational material (Padlet) and the creation of a user group on Viber for faster communication between us began. The entry questionnaire, which was part of the evaluation of the program, was completed. Then, the structure of the program was presented to the trainees and a presentation and discussion of the basic principles of the gamified and student-centered approach to teaching subjects was held. Shortly before the closing of the day and its evaluation, the trainees were introduced to the digital application “Learning designer”, which would be the tool for writing educational scenarios.

During the second day, and after the relevant recapitulation of the previous day's experiences, a scenario was implemented on the dibl platform with the aim of a first acquaintance with both the dilemma in teaching and the environment of the platform itself. Then, a presentation of the principles of dilemma-based learning was made with parallel discussions on the issues raised. Most of the day was dedicated to the experience approach and engagement with strategies and tools of student-centered and playful learning. Thus, the "Save the last word" technique was presented through the online application "Answergarden", with the aim of searching on the part of the participants the motivation that made one or another participant submit a specific word to the question: "What word comes to mind when you hear the word freedom?". The trainees then engaged in the "Fishbowl debate" technique. The question was whether "school kills creativity" or not and the participants had to discuss it initially at the level of an inner circle group with the other observers, and then at the plenary level. They also got acquainted with perhaps the most classic tool of playful learning, the online application Kahoot. There they answered a quiz that had been created for the purposes of the seminar and experienced, experientially, the possibilities provided by this specific application for creating quizzes in an intensely playful environment. They then competed in a "Debate" under the title "Game Fighters vs. Game Lovers", presenting arguments for or against the use of gamification during teaching. Before the evaluation of the day, they engaged in the "Think–Pair–Share" technique with the aim of approaching it from the inside on a practical level to the question: "Should a school participate in the Erasmus program or not?" There they thought, initially alone, then discussed in pairs and finally discussed in plenary on the above topic.

On the third day, after the plenary session presented student-centered actions that the trainees themselves had implemented in their classroom, there was a discussion about the prevailing climate and the way in which the students experienced the specific applications. The rest of the day was dedicated to the admittedly demanding task of learning how to use the dibl platform. The trainer had already invited and registered users on the platform and presented the management environment, the way it works and the various features of the platform (capturing a dilemma, sharing a dilemma with students, formulating closed and open-ended questions, recording “scores”, creating groups). The trainees were then asked to start preparing a first dibl scenario. For this reason, they had already been guided the previous day to start thinking about how they could utilize the dilemma in a thematic unit of their subject.

The fourth day was dedicated entirely to the design of the student-centered lesson scenario while simultaneously becoming familiar with the use of the dibl platform. The trainees, either in groups or in plenary, exchanged views on the scenarios they were thinking of implementing, the strategies they were going to incorporate and, more generally, on ways of structuring a scenario based on the objectives of this program. The main concern, of course, was the adequate understanding of how the dibl platform works by everyone, as the utilization of this specific platform, being one of the deliverables of the training, was going to be included in the final scenario.

The last day was dedicated to the presentation of some of the scenarios that had already been prepared, albeit in a preliminary form, and feedback on the practices that were followed. The exit questionnaire was completed and the trainees evaluated the seminar they attended with a relevant questionnaire via the Google Forms application.

It should be noted here that, in general, the trainer-trainee collaboration had begun one week before the start of each seminar, in a remote introduction-information meeting. At the same time, two more remote meetings were held: The first two weeks after the end of the seminar with the aim of informing each other and providing feedback on the final scenarios that had been submitted, and one just before the end of the school year, with the aim of exchanging views arising from the implementation of the scenarios and their evaluation by the teachers and students themselves.

From the study of the quantitative data of the training program in its entirety is recorded the participation of 177 Primary and Secondary Education teachers, of which 113 were members of the pedagogical teams of the Erasmus+ program partners. At the same time, a corresponding number of teaching scenarios were designed, implemented and evaluated which combine principles, at a theoretical level, and activities, at a practical level, of student-centered learning, gamification and dilemma-based learning while, of course, utilizing the dibl platform.

3.2 Evaluation - conclusions

For the overall evaluation of the training program were used the entry and exit questionnaires, the seminar evaluation form and the evaluation rubrics designed by the trainees in the context of the implementation of the scenarios and completed by both the trainees themselves and the students involved. From the study of the entry and exit questionnaires, it seems that a remarkable improvement is recorded in the knowledge and skills of the trainees on issues related to studentcentered learning, gamification and dilemma-based learning. From the program evaluation form, a positive image of the trainees is observed both for the content and the design and implementation of the training activities. Despite any initial difficulties in handling the dibl platform, it is ultimately recorded that the trainees made adequate use of it and that the technical problems were rather small-scale and completely manageable. Also, the fruitful and creative combination of digital and non-digital tools within the framework of the seminar in general is recorded. Perhaps the most important criterion for the evaluation of the training program was the opinions of the teachers and students themselves, which were recorded after the implementation of the teaching scenarios. The teachers' pleasant mood is observed due to their engagement with innovative practices that serve the goals of each subject. They experienced the new facilitatingguiding role of the modern teacher, who coordinates the curriculum taking into account the identities and experiences of the students and utilizes the available resources in an open creative learning environment with an emphasis on the cultivation of critical thinking. At the same time, they noted a change in the climate in the classroom and a broader mobilization of the students, resulting in their more active participation in the educational process. And the students themselves, for their part, in the self-assessment rubrics they completed, expressed their enthusiasm for participating in activities that were different and more fascinating than those they had experienced so far during their previous school years.

Based on the above data, it can be argued that the opinion of those benefiting from the training program “Student-centered and gamified learning. Exploiting the dilemma – dibl” is positive. This observation demonstrates the smooth achievement of the program’s objectives and the success of its implementation. It seems to leave behind, as a legacy, innovative practices and modern educational procedures in the service of goal-setting in various primary and secondary education subjects.

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NMPC and Deep Learning-based Vibration Control of Satellite Beam Antenna Dynamics Using PZT Actuators and Sensors

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A B S T R A C T

This paper presents a novel approach for vibration control of satellite-based flexible beam-type antennas using Nonlinear Model Predictive Control (NMPC) and Deep Learning techniques. The developed control system leverages piezoelectric (PZT) actuators and sensors to manage the coupled attitude and structural dynamics of the satellite, improving precision and stability. We propose a detailed coupled dynamics model that integrates both satellite attitude and beam structural dynamics, considering the effects of PZT-based actuators. Through MATLAB/Simulink simulations, we demonstrate the effectiveness of the combined NMPC and Deep Learning framework in reducing structural vibrations, achieving faster response times, and enhancing overall control accuracy. The results indicate that the proposed system provides a robust solution for controlling flexible beam-type satellite antennas in space environments.

Keywords: NMPC, deep learning, vibration control, piezoelectric (PZT) actuators and sensors, structural dynamics

1. INTRODUCTION

In modern satellite systems, the increasing demand for higher data transmission rates and efficient communication capabilities has led to the use of flexible beam-type antennas. These antennas, while highly efficient, are prone to structural vibrations due to their flexibility, which can significantly degrade performance. Controlling these vibrations is critical, particularly when the dynamics of the satellite's attitude are coupled with the vibrations of the antenna. The integration of advanced control techniques such as Nonlinear Model Predictive Control (NMPC) and Deep Learning, along with the use of piezoelectric (PZT) actuators and sensors, represents a promising avenue for solving this challenge.

Several studies have tackled the issue of vibration control in satellite systems. Ji et al. (2024) proposed an adaptive fault-tolerant control framework for flexible satellites, reducing vibration through an event-triggered mechanism based on a PDE model (Ji, 2024). Similarly, Callipari et al. (2022) investigated Offset Piezoelectric Stack Actuators (OPSA) for enhanced damping in space structures, outperforming conventional piezoelectric patches (Callipari, 2022).

Active vibration control (AVC) has also been explored extensively. Smith and Johnson (2018) reviewed various AVC strategies for large flexible space structures, highlighting the use of PZT actuators to minimize vibrational disturbances (Smith, 2018). Angeletti et al. (2020) introduced a distributed network of actuators and sensors, showing that optimal actuator placement significantly reduces deformations during attitude maneuvers (Angeletti, 2020). Similarly, Lee et al. (2020) applied AVC to large flexible satellite structures using PZT sensors and actuators (Lee, 2020). Zhang et al. (2020) demonstrated adaptive vibration control using fixed-time prescribed performance control, achieving high precision during dynamic satellite operations [Zhang, 2020]. The integration of Deep Learning into control strategies has garnered significant attention. Qiu and Wang (2021) developed neural network models for adaptive control, demonstrating that deep learning can predict optimal control inputs based on past vibration data (Qiu, 2021). Sun and Li (2021) further showed that combining deep learning with NMPC can optimize real-time control, leading to improved satellite stability (Sun, 2021). Zhou et al. (2020) also emphasized the role of deep learning in optimizing control algorithms for large, flexible satellite structures (Zhou, 2020).

The role of PZT actuators and sensors has been studied extensively. Karami and Daneshmand (2019) explored the enhancement of attitude control and vibration mitigation through PZT actuators (Karami, 2019). Abdo and Kaddouh (2021) examined the nonlinear behavior of PZT patches in vibration suppression, concluding that smart materials play a pivotal role in modern satellite control systems (Abdo, 202). Wang et al. (2021) proposed a hybrid system integrating PZT sensors with NMPC to improve vibration suppression in flexible satellite appendages (Wang, 2021). Sharma et al. (2020) highlighted the potential of piezoelectric smart materials in creating self-regulating satellite structures capable of mitigating vibrations autonomously (Sharma, 2020).

Despite these advances, challenges remain in optimizing actuator placement and fully integrating NMPC with smart materials. Park and Shin (2021) called for more research into optimizing actuator placement for smart materials to fully exploit their capabilities in vibration control (Park, 2021). Tang and Zhou (2019) emphasized the need for improved placement strategies for smart actuators to better manage vibrational modes in flexible structures (Tang, 2019).

Furthermore, deep learning presents a promising solution to many of these challenges. Zhao and Cheng (2020) discussed how deep learning could improve real-time control in rapidly changing space environments, where traditional models struggle (Zhao, 2020). Zou and Li (2019) explored how reinforcement learning can be integrated with control systems to adapt to environmentaluncertainties and improve vibration suppression during satellite operations (Zou, 2019). Kumar and Nair (2019) reviewed optimization strategies for controlling vibrations in flexible space antennas, stressing the importance of adaptive control for mission success (Kumar, 2019). Lee and Han (2021) demonstrated that predictive control algorithms integrated with machine learning can further stabilize satellite systems with flexible appendages (Lee, 2021).

In parallel, Li and Chen (2020) explored how NMPC integrated with PZT sensors can improve control precision in satellite applications, particularly in flexible structures [Li, 2020]. Anderson and Zhang (2020) modeled the coupled dynamics of smart actuators in flexible satellites, revealing the significant improvements in stability and performance achieved by integrating PZT actuators with NMPC (Anderson, 2020). Wu and Feng (2022) highlighted how advanced PZTbased control systems can manage large-scale structures under real-time operational conditions (Wu, 2022).

Lastly, integration of advanced optimization strategies and smart actuator networks was examined by Park and Kim (2020), who showed that integrating PZT sensors into attitude control systems improves precision, especially during high-frequency disturbances (Park, 2020). Zhao and Cheng (2020) further emphasized the role of deep learning in dynamically controlling flexible structures, providing solutions to challenges in space environments (Zhao, 2020). Gao and Yu (2018) focused on finite element modeling to optimize flexible satellite structures, highlighting the significance of accurate structural simulations for control system design (Gao, 2018).

In conclusion, significant progress has been made in the development of control strategies for flexible satellite antennas. However, challenges remain, particularly in integrating NMPC, deep learning, and PZT actuators. This paper aims to address these gaps by proposing an integrated control system leveraging these advanced technologies for precise vibration suppression and satellite attitude stabilization.

This paper is organized as follows: In Section 2, a detailed introduction to the system is provided, covering the spacecraft's geometric configuration, including its flexible components and structural dynamics. Section 3 delves into the forces and moments generated by piezoelectric actuators. Section 4 outlines two innovative control approaches for vibration mitigation: the NMPC model and the NARX-based control method, explaining the theoretical foundations and implementation procedures for each. Section 5 discusses the results, comparing the performance of the proposed control techniques against conventional methods under different disturbance scenarios. Finally, Section 6 summarizes the key findings of the research, highlights their significance, and proposes potential practical applications.

2. Overview of the Sytem

Our research examines a rigid spacecraft equipped with n slender, deformable appendages integrated with piezoelectric (PZT) control elements. Figure 1 illustrates this setup, showcasing a specific example in which two elastic beams are attached to the central body. The piezo-ceramic actuators and strain sensors, either bonded to or embedded within the spacecraft's appendages, are depicted in Figure 2.

The vibration equations for a beam-type structure are derived using the Lagrangian formulation. In this approach, the kinetic energy (T), potential energy (V) of the beam, and the generalized forces generated by the piezo-ceramic actuators are systematically calculated.

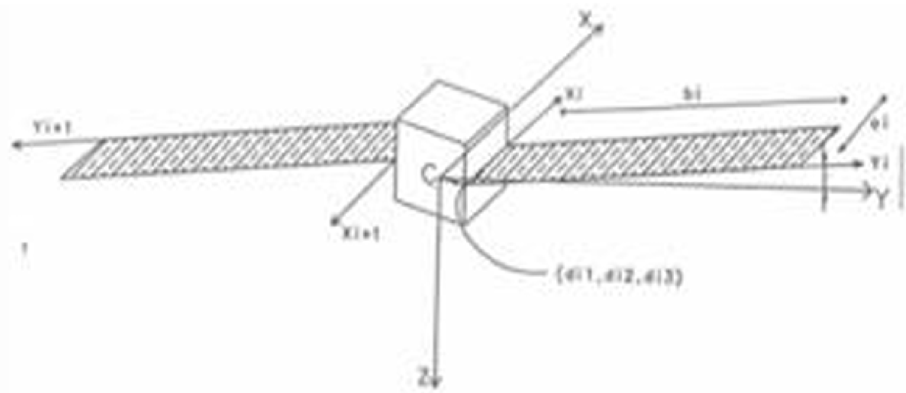

Figure 1 Satellite with flexible beam-type appendages

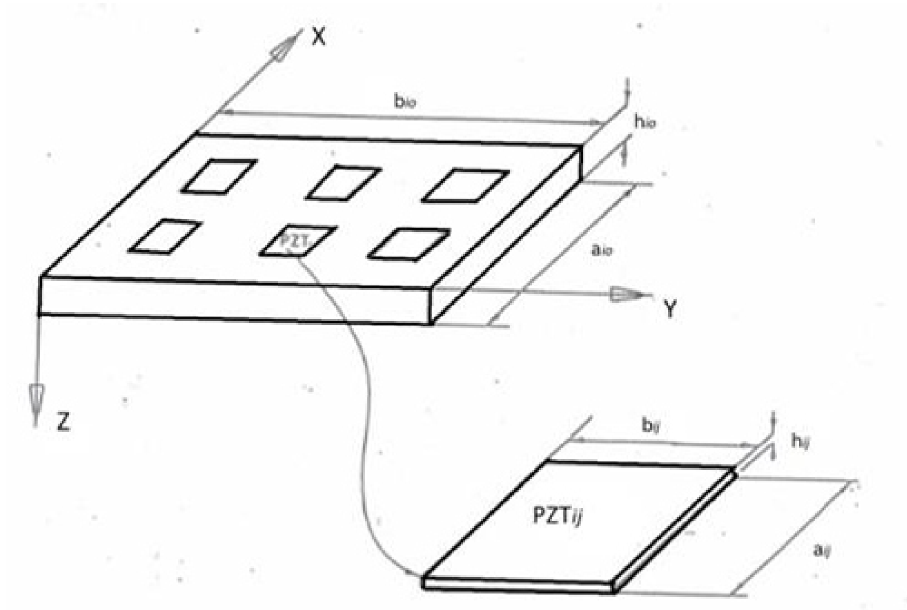

Figure. 2. Geometry of the beam and the piezo-ceramic actuators

The transverse displacement of the beam, denoted as u(yi,t), occurs along the z-direction for the ith appendage. For ease of analysis, the elastic displacement u is expressed as a series expansion, as follows:

$$u_i(y_i, t) = \sum_{s=1}^{n_s} W_{is}(t)\psi_s(y_i) = W^T \vec{\Psi}_i \qquad (1)$$

The spatial functions ψs(yi) constitute a complete orthogonal set that satisfies the structural boundary constraints. Increasing ns enhances the accuracy of the approximation, allowing convergence toward the true displacement field. In practical applications, selecting appropriate ψs(yi) facilitates accurate representation through truncated series expansions. The natural modes of fixed-free structural elements are particularly effective as basis functions for ψs(yi), as these eigen-solutions inherently satisfy both geometric and force boundary conditions while preserving orthogonality within the solution domain.

The kinetic energy of the beam, T can be written as:

$$T = \frac{1}{2}\int_0^{b_i} (\dot{\vec{R}}_i)^T \cdot (\dot{\vec{R}}_i)\frac{m_i}{b_i}\, dy_i \qquad (2)$$

where mi is the mass density per unit length in the y-direction and Ri is the velocity of any point on the beam.
The strain energy stored in the beams can be expressed as:

$$U = \frac{1}{2}\sum_{i=1}^{n} D_i \int_0^{b_i} \left[\left(\frac{\partial^2 u_i}{\partial y_i^2}\right)^2\right] dy_i \qquad (3)$$

where

$$D_i = \frac{E_{io}h_{io}^3}{12(1-\nu^2)}$$

The parameter ν is the Poisson ratio. Di represents the flexural rigidity of the beam, associated with its transverse displacement along the z-axis. The governing equations for the beam's vibrations are derived using the Lagrangian formulation, as follows:

$$\frac{d}{dt}\left[\frac{\partial T}{\partial \dot{W}_{is}}\right]-\left[\frac{\partial T}{\partial W_{is}}\right]+\left[\frac{\partial U}{\partial W_{is}}\right]=\vec{F}_i \qquad (4)$$

The index s ranges from 1 to nr, where nr represents the truncation order in the spectral decomposition for clamped-free (C-F) boundary conditions. The term Fi corresponds to the generalized modal force components.

The generalized modal force components Fi account for contributions from external disturbances, dissipative effects, and controlled actuation inputs. Consider a distributed environmental load p(yi,t) acting normal to the surface of the i-th flexible member, alongside discrete control forces τr applied perpendicularly at specific points yir, measured from the member's base. The resulting modal forcing function can be expressed as:

$$\vec{F}_i=\int_0^{b_{io}} p(y_i,t)\psi_j\,dy_i+\sum_{r=1}^{p}\tau_r\psi_j(y_{jr})+\vec{F}_{ds} \qquad (5)$$

The dissipative force component Fds is represented as a linear function of the generalized velocity capturing uncoupled viscous energy dissipation in the modal domain. By incorporating the derived energy expressions into the variational formulation and carrying out the necessary mathematical derivations, the following result is obtained:

$$\ddot{\vec{W}}_i+D_{wi}\dot{\vec{W}}_i+K_i\vec{W}_i=\vec{F}_i \qquad (6)$$

which governs the vibrations of the beam, Dwi is the damping matrix and is assumed to be diagonal. Fi represents the generalized forces due to the piezo-ceramics actuator control forces Fc and the other dynamics forces including the external disturbances Fd:

$$\vec{F}_i=\vec{F}_c+\vec{F}_d \qquad (7)$$

The subsequent analysis focuses on evaluating Fc specifically for piezo-ceramic actuators.

3. Generalized Moments and Forces Created by Piezoceramics Actuators

The stress in the PZTij can be written as:

$$\sigma_{ij}=E_{ij}(\epsilon_{io}+\epsilon_{ij}) \qquad (8)$$

where Eij represents the modulus of elasticity, ϵij is the strain in the PZTij (caused by the applied voltage), and ϵio is the longitudinal strain in the beam due to force balance. The strain ϵij can be characterized by:

$$\epsilon_{ij}=\frac{d_{31}V_{ij}(t)h_{ij}}{b_{ij}} \qquad (9)$$

where d31 is the PZT electric coefficient, hij represents the thickness of PZTij, and Vij(t) denotes the voltage applied to
PZTij.

Application of force equilibrium principles to the differential element yields:

$$E_{ij}h_{ij}b_{ij}(\epsilon_{ij}+\epsilon_{io})+E_{io}h_{io}b_{io}\epsilon_{io}=0 \qquad (10)$$

Thus, the longitudinal strain ϵio is:

$$\epsilon_{io}=\frac{E_{ij}h_{ij}}{E_{ij}h_{ij}+E_{io}h_{io}}\epsilon_{ij} \qquad (11)$$

Through moment balance analysis of PZTij and utilizing the constitutive relationships of Eq. (11) that couple ϵio and ϵij with the temporal voltage signal Vij(t), one obtains:

$$M_{ij}(y,t)=\frac{d_{31}E_{io}h_{io}E_{ij}(h_{ij}+h_{io})}{2(E_{io}h_{io}+E_{ij}h_{ij})^2} \times\left[E_{io}h_{io}a_{ij}+E_{ij}h_{ij}a_{io}\right]V_{ij}(t) \qquad (12)$$

$$M_{ij}(y,t)=P_{yij}\cdot V_{ij}(t) \qquad (13)$$

Thus, Upij can be written as:

$$U_{pij}=-\frac{1}{2}\int_{A_{ij}}\left[P_{yij}\cdot V_{ij}(t)\left(\frac{\partial^2 u}{\partial y^2}\right)\right]dx\,dy \qquad (14)$$

The total strain energy associated with the PZT-generated moments can be expressed as:

$$U_p=-\frac{1}{2}\sum_{i=1}^{n}\int_{A_{ij}}\left[P_{yij}\cdot V_{ij}(t)\left(\frac{\partial^2 u}{\partial y^2}\right)\right]dx\,dy \qquad (15)$$

Incorporating the Up into the Lagrangian equation, one can obtain Fc, the control force created by the PZTij actuators on the ith beam:

$$\vec{F}_c=\frac{1}{2}\sum_{j=1}^{m}\frac{V_{ij}}{a_{ij}b_{ij}}\left[P_{yij}\vec{C}(x_{ij},y_{ij})\right] \qquad (16)$$

$$\vec{C}=\int_{\xi_j-\frac{b_j}{2b_o}}^{\xi_j+\frac{b_j}{2b_o}}\Psi''d\xi \qquad (17)$$

where m is the number of PZT actuators on the appendage I.

4. Control Models

In this section, two innovative control techniques are developed and applied to the vibrational dynamics model of a satellite with PZT-mounted beam-type appendages. The initial method employed is Nonlinear Model Predictive Control (NMPC), which leverages a predictive model of the system's dynamics to determine optimal control actions over a limited future timeframe. The second technique is an AI-based Nonlinear AutoRegressive with eXogenous inputs (NARX) control method, which operates without requiring an explicit mathematical model of the system dynamics.

4.1 NMPC Model

This section presents the Nonlinear Model Predictive Control (NMPC) model for the coupled structural and vibrational control of PZT-mounted beam-type satellite appendages. The conventional MPC formulation for this system is given by (Kalaycioglu and de Ruiter, 2023):

$$\min \int_0^{T_p} \Big((\vec{y}(t) - \vec{y}_r(t))^T K_y (\vec{y}(t) - \vec{y}_r(t)) + \vec{S}^T(t) K_s \vec{S}(t) \Big) dt \quad (18)$$

subject to:

$$\dot{\vec{y}} = \vec{g}(\vec{y}) + L\vec{S}, \quad \text{and} \quad \vec{z} = \vec{g}_z(\vec{y}) + H\vec{S} \quad (19)$$

$$\vec{y}(0) = \vec{y}(t_0) \quad (20)$$

$$\vec{S}_{\min} < \mathbf{\Lambda}\vec{S} < \vec{S}_{\max} \quad (21)$$

where the prediction horizon is denoted by Tp, and the weighting matrices Ky and Ks are positive definite. The functions $\vec{g}(\vec{y})$, $\vec{g}z(\vec{y})$, L, and H originate from the nonlinear system equations in Eqs. (6) and (16). The matrix Λ serves as a positive definite scaling matrix, used to adjust for the saturation limits.

Upon discretization of the system equations, one can obtain the following difference equations:

$$\vec{y}(k+1) = \hat{A}(\hat{g}(k))\vec{y}(k) + \hat{B}(\hat{g}(k))\vec{S}(k) \quad (22)$$

$$\vec{z}(k) = \hat{C}(\hat{g}_z(k))\vec{y}(k) + \hat{D}(\hat{g}(k))\vec{S}(k) \quad (23)$$

$$\hat{g}(k) = f_g(\vec{y}(k)) \quad (24)$$

$$\vec{S}_{\min} \leq \mathbf{\Lambda}\vec{S}(k) \leq \vec{S}_{\max} \quad (25)$$

At the discrete time step k, the output vector $\vec{z}(k)$ is obtained from measurements taken at that specific moment. The matrices in Eqs. (22-25) are provided in Kalaycioglu and de Ruiter (2023). At every sampling point, the NMPC algorithm calculates the discrete state variables $\vec{y}(k)$ and control signals S(k) by optimizing the following cost function:

$$C_n = \frac{1}{2}\sum_{j=1}^{N_P} \Big((\vec{y}(k+j) - \vec{y}_r(k+j))^T \times K_y (\vec{y}(k+j) - \vec{y}_r(k+j)) + \vec{S}(k+j-1)^T K_s \vec{S}(k+j-1) \Big) \quad (26)$$

subject to:

$$\vec{y}(k+j+1) = \hat{A}(\hat{g}(k+j))\vec{y}(k+j) + \hat{B}(\hat{g}(k+j))\vec{S}(k+j) \quad (27)$$

$$\vec{z}(k+j) = \hat{C}(\hat{g}(k+j))\vec{y}(k+j) + \hat{D}(\hat{g}(k+j))\vec{S}(k+j) \quad (28)$$

$$\vec{S}_{\min} \leq \mathbf{\Lambda}\vec{S}(k+j) \leq \vec{S}_{\max} \quad (29)$$

However, when constraints are active, the optimal control solution cannot simply be derived by setting the derivative of the cost function to zero. Instead, the optimality conditions must be derived based on the Karush-Kuhn-Tucker (KKT) conditions, which take into consideration the constraints on the control inputs.

To solve the optimization problem and satisfy the KKT conditions, the MATLAB Quadratic Programming (QP) solver is used. The QP solver automatically incorporates the constraints from Eq. (21), ensuring that the control inputs respect the bounds and minimize the cost function subject to these constraints.

The QP solver minimizes the following quadratic cost function:

$$C_n = \frac{1}{2}\sum_{j=1}^{N_p}\left[\vec{S}(k+j)^T\hat{P}\vec{S}(k+j) + 2(\vec{g})^T\,\vec{S}(k+j)\right] \quad (30)$$

where:

$$\hat{P} = (\hat{B}^T K_y \hat{B} + K_s) \quad (31)$$

$$(\vec{g})^T = \left(\vec{y}(k+j)^T \hat{A}^T K_y \hat{B} - \vec{y}_r(k+j)^T K_s \hat{B}\right) \quad (32)$$

By using the QP solver, the control inputs are guaranteed to satisfy the KKT conditions, ensuring that the solution is optimal while adhering to the constraints.

The result is a robust NMPC formulation that effectively controls the structural and vibrational dynamics of satellite appendages equipped with PZT actuators, achieving the desired performance while respecting input constraints.

4.2 NARX-Based Control for Vibration Suppression of PZT Mounted Beam-Type Satellite Appendages

The NARX (Nonlinear AutoRegressive with eXogenous inputs) model is an AI-based method for system identification and control, particularly suitable for complex, nonlinear systems where traditional modeling approaches may be inadequate (He, 2015 and Song, 2023). Unlike NMPC, the NARX model does not require an express analytical model of the system, making it highly versatile and adaptive. In the context of vibration suppression for PZT-mounted beam-type satellite appendages, the NARX model is employed to estimate the system states and predict the required control actions. The control inputs, consisting of the PZT control forces are determined based on the predicted system outputs.

NARX neural networks offer a promising framework for controlling systems characterized by high nonlinearity and the need for adaptability. NARX-based control utilizes the network's capacity for inverse dynamics control, directly learning the inverse dynamics model to achieve a unity transfer function between the actual and desired output.

One of the significant advantages of using NARX-based control is its adaptive nature. The model can be updated online as new data becomes available, allowing it to adjust to changes in system dynamics and external disturbances. This functionality proves to be especially advantageous in space missions, where unpredictable conditions frequently arise (Roghanchi, 2019).

The adaptive control strategy can be described as follows:
(i) Continuously collect real-time data from the satellite's sensors.
(ii) Periodically retrain the NARX model with the latest data to capture any changes in the system's behavior.
(iii) Update the control inputs based on the updated model predictions

The proposed approach augments the standard NARX architecture with a neural network discriminator (NND) (Song, 2023). This NND serves as an online learning mechanism, continuously refining the NARX model's connection weights by discriminating between inputoutput pairs obtained in real time. This dynamic adaptation significantly enhances the controller's robustness to external disturbances and system parameter variations, addressing a key limitation of traditional direct inverse control.

By embedding the NND within the control strategy, the NARX-based system maintains high performance and precision even under unpredictable conditions. This makes it particularly wellsuited for applications where adaptability and robustness are critical, such as spacecraft and robotics in complex dynamic environments. The key advantages include the following:
(i) Nonlinearity: NARX models inherently capture complex nonlinear relationships between system inputs and outputs.
(ii) Adaptability: The NND enables online learning, ensuring continuous model refinement in response to changing conditions.
(iii) Robustness: The dynamic nature of the control strategy provides resilience to external perturbations and parameter drift.
4.2.1 Model Formulations
The NARX model predicts the future states of a system based on past inputs and outputs. The general form of the NARX model can be expressed as:

$$y(t+1) = h\Big(y(t), y(t-1), \ldots, y(t-d_y), S(t), S(t-1), \ldots, S(t-d_s)\Big) \quad (33)$$

where y(t) is the output at time t, S(t) is the input at time t, dy is the maximum lag in the output, and ds is the maximum lag in the input.
The mathematical formulation of the NARX-based control can be expressed as:

$$\vec{y}(t+1) = \bar{\bar{A}}\vec{y}(t) + \bar{\bar{B}}\vec{S}(t) \quad (34)$$

$$\vec{z}(t) = \bar{\bar{C}}\vec{y}(t) + \bar{\bar{D}}\vec{S}(t) \quad (35)$$

where A, B, C, and $\bar{D}$ are matrices obtained from the trained NARX model.

4.2.2 Implementation

The NARX-based control is implemented as follows:
(i) Collect historical data of the system outputs $\vec{y}(t)$ and inputs S(t).
(ii) Train the NARX model using this data to capture the system dynamics.
(iii) Use the trained NARX model to predict future states $\vec{y}(t+1)$ based on current and past states and inputs.
(iv) Compute the control inputs S(t) required to achieve the desired system performance.

4.2.3 Training and Validation

The NARX model can be trained using either actual historical data or simulated data from a developed dynamics model. This training process optimizes the model's weights and biases to minimize the prediction error between the model's output and the actual observed output. Commonly employed algorithms for this optimization include Levenberg - Marquardt back propagation and Bayesian regularization, which are known to enhance the model's robustness and generalization capabilities (Rahrooh, 2009; Yan, 2016 and Kelley, 2024). The training process can be summarized as follows:

(i) Collect a comprehensive dataset of system inputs S(t) and outputs $\vec{y}(t)$.
(ii) Preprocess the data to remove noise and normalize values.
(iii) Initialize the NARX network with a suitable architecture, typically including several hidden layers and neurons.
(iv) Train the network using a portion of the dataset, employing either the Levenberg-Marquardt algorithm or Bayesian regularization.
(v) Assess the performance of the trained model on a distinct validation dataset to verify its ability to generalize effectively to new, unseen data.

5. Results and Discussion

The proposed NMPC and NARX-Inverse Dynamics based control approach were evaluated through MATLAB/Simulink simulations. Figure 3 illustrates the control block diagram.
Performance of the two methods and that of the PD control were compared under various disturbance conditions, demonstrating effective vibration suppression in the flexible appendages. Notably, NMPC performance was dependent on model accuracy, while the NARX approach proved more effective under model uncertainties and disturbances. Key metrics included vibration amplitude reduction, response time, and stability under varying conditions.

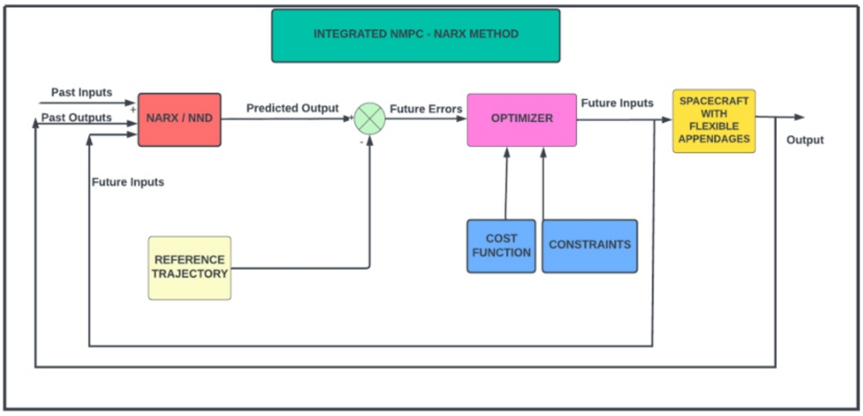

Figure 3. NMPC-NARX control method

A comprehensive case study was performed on a satellite equipped with beam-type appendages mounted with PZTs. The NMPC method utilized the developed structural dynamics model, while the NARX model was trained on historical data and PZT voltage-induced structural motions. The trained NARX model was subsequently employed and constantly updated with the support of the neural network discriminator (NND). This NND served as an online learning mechanism to predict the control inputs necessary for vibration suppression and attitude maintenance while the system was subject to disturbances.

Simulation results showed that both NMPC and NARX based control methods outperformed a traditional control strategy like PD control, providing faster response times and better vibration suppression in the case of existence of significance dynamics model uncertainties and disturbances. These findings demonstrated the potential of NARX models for advanced vibration control in space applications.

5.1 Simulation Setup, Network Configuration and Training

The simulation setup involved creating a detailed structural dynamics model of the satellite with PZT-mounted beam-type appendages in MATLAB/Simulink. The NARX and NND models were also integrated into this simulation environment to evaluate its performance under various conditions.

The NARX neural network was configured with input delays ranging from 1 to 2-time steps and feedback delays also spanning from 1 to 2 time steps. This configuration allows the network to utilize both recent and slightly older input and output values to predict future outputs, capturing the temporal dynamics of the system effectively. The network architecture included a single hidden layer consisting of 10 neurons, utilizing ReLU as the activation function. This selection was made to achieve an optimal balance between the complexity of the model and the efficiency of computation.
The network was trained using the Levenberg-Marquardt algorithm, an optimization method known for combining the strengths of both the Gauss-Newton and gradient descent approaches. This algorithm enhances convergence speed and improves the network's ability to reach an optimal solution, making it particularly effective for neural network training.

The dataset was split into three distinct subsets: training, validation, and testing. The training subset was used to update the network's weights and biases, while the validation subset monitored the training process to prevent over fitting by assessing the network's performance after each epoch. Finally, the test subset was reserved for evaluating the network's generalization performance on unseen data once the training was completed.

The performance of the network was evaluated using the Mean Squared Error (MSE) metric, which calculates the average of the squared differences between predicted and actual values. This metric offers a clear assessment of the network's accuracy, where lower MSE values reflect higher prediction precision and better overall performance.

The main parameters for the simulation were a sampling time of 0.01 seconds, a prediction horizon spanning 10 steps, and a control horizon of 5 steps. The disturbance scenarios examined included random vibrations, sudden impacts, and persistent external forces.

To comprehensively assess the NMPC and NARX-based control, a range of disturbance scenarios were considered. These included random vibrations to simulate low-magnitude disturbances and evaluate the control's ability to manage minor perturbations, sudden impacts to assess responsiveness and stability under high-magnitude forces, and continuous external forces The available measurements included sensor data on vibration amplitudes and system response times, which were crucial in evaluating the control strategies. Measurement noise was explicitly modeled in the simulation to reflect real-world conditions, with Gaussian noise added to the vibration and impact sensor data, characterized by a standard deviation of 0.05 and a mean of zero. The disturbances were also carefully modeled: random vibrations were generated using a white noise process with a standard deviation of 0.1 and a bandwidth of 5 Hz, while sudden impacts were simulated as impulse forces with magnitudes ranging from 5 N to 20 N. Continuous external forces were applied as sinusoidal functions with frequencies ranging from 0.5 Hz to 2 Hz and amplitudes from 0.2 N to 1 N to test long-term stability. The NARX neural network inherently accounted for system dynamics and provided accurate predictions based on the input-output data.

Performance was evaluated using key metrics such as vibration amplitude reduction, response time, and stability.

The detailed parameters of the PZT sensors and actuators, spacecraft, and the flexible beam-type appendages utilized in the simulations are listed in Table 1.

Table 1. Physical parameters for the system

Parameter	Values	Unit
beam Dimensions (a_{io}, b_{io}, h_{io})	$(0.3, 1, 2 \times 10^{-3})$	m
PZT Dimensions (a_{ij}, b_{ij}, h_{ij})	$(0.1, 0.1, 0.5 \times 10^{-3})$	m
Young's Modulus of Elasticity beam and PZT E_{io}, E_{ij}	6.9×10^{10}	Pa
The Locations of PZTs (x_{ij}, y_{ij})	$[(0.1, 0.1), (0.5, 0.1), (0.9, 0.1)]$	m
Poisson's Ratio	0.33	none
Density of the beam ρ	2.7×10^3	kg/m^3
PZT Electric Coefficient d_{31}	-1.75×10^{-10}	V^{-1}
Moments of Inertia of Satellite	$\begin{bmatrix} 1.2 & -0.05 & -0.03 \\ -0.05 & 3.02 & -0.02 \\ -0.03 & -0.02 & 8.02 \end{bmatrix}$	kg-m^2

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The elastic deformation of the beam was discretized and expanded in terms of modal shape functions. The shape functions for the beam were obtained from the eigenfunctions of a clamped-free (cantilever) beam. Figure 4 illustrates the mode shapes for a clamped-free beam.

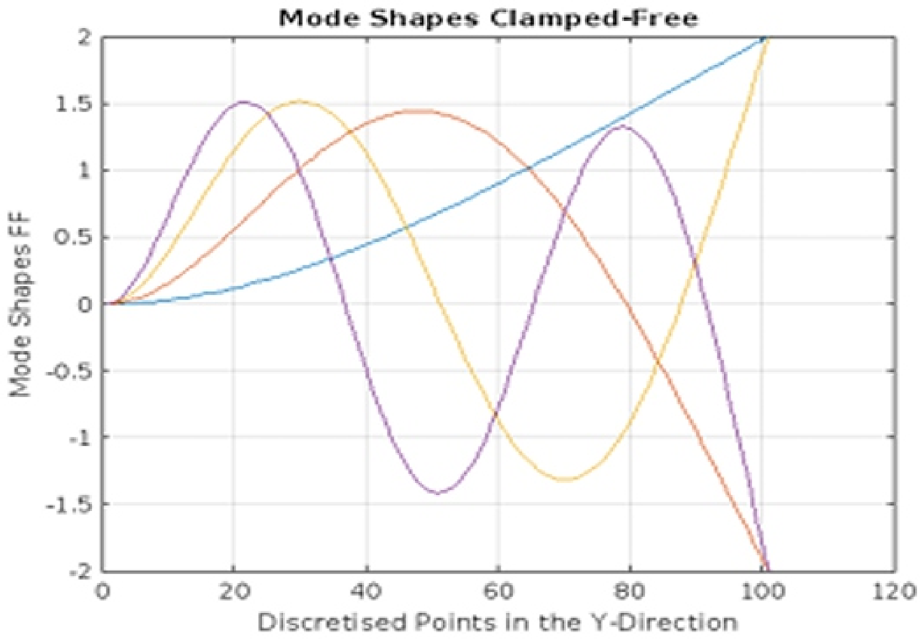

Figure 4. Eigenshapes for a Clamped-Free beam

5.2 Results of the NMPC Method

Figure 5 demonstrates the time histories of the first three modal time coefficient functions for both NMPC and PD control methods. Across all three cases, the NMPC method exhibited superior performance in suppressing vibrations compared to the PD control. Specifically, the modal time coefficient functions under NMPC displayed faster decay rates and smaller amplitudes, indicating more rapid and effective vibration suppression.

The visual representation clearly shows that the NMPC method consistently outperforms the PD control across all modes, highlighting its robustness and reliability in various operational conditions. These characteristics suggest that the NMPC method is more efficient at damping out oscillations, thereby stabilizing the system more quickly.

Figure 6 presents the time variation of the PZT modal force, Fc, for both NMPC and PD control methods. The NMPC method produced smoother and more controlled PZT forces compared to the PD control, which exhibited higher frequency oscillations. This observation suggested that NMPC can achieve better vibration suppression with less aggressive control actions, potentially leading to reduced energy consumption and less wear on the PZT actuators. The smoother force profile under NMPC indicated that the actuators were subjected to less stress, which could enhance their longevity and reduce maintenance requirements.

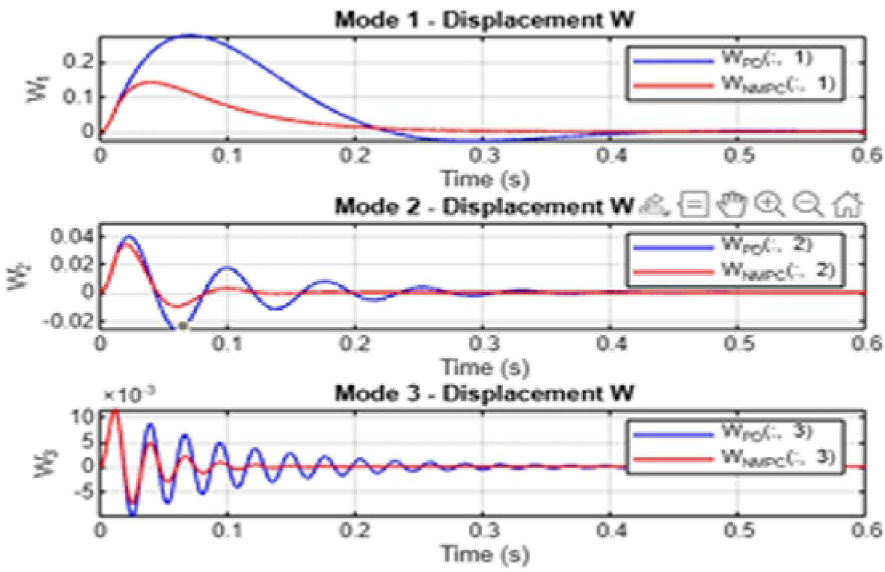

Figure 5. comparison of modal time coefficient functions for NMPC and PD control methods

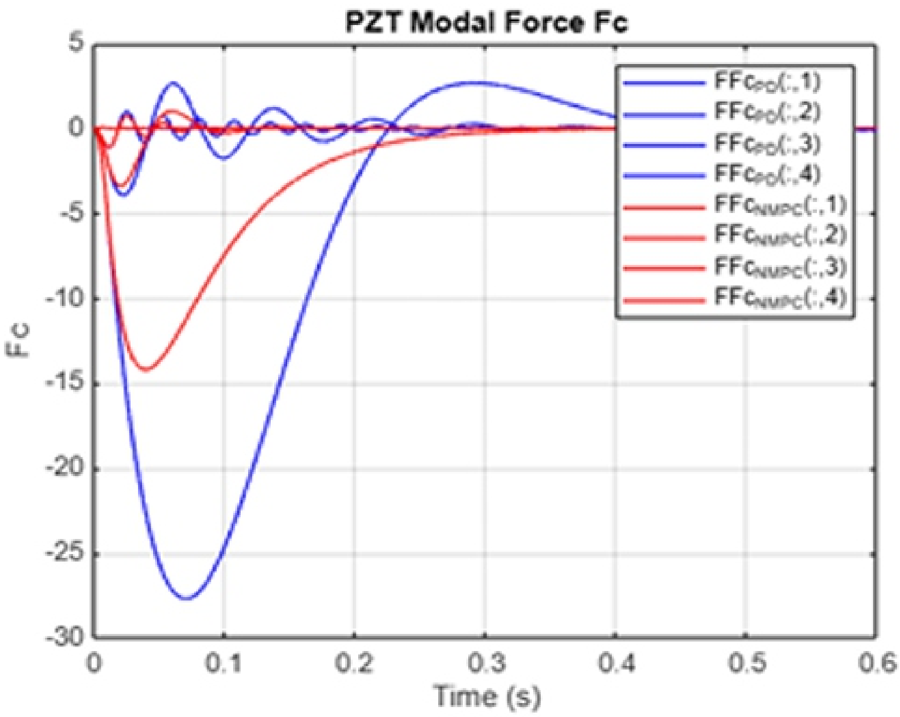

Figure 6 Time variation of PZT Modal Force Fc under NMPC and PD control

5.3 Results of the NARX Method

Figure 7 compares the time-varying modal coefficients for both NARX and a traditional PD control under conditions of model uncertainty and disturbances. The NARX method produced superior results compared to the PD control, which exhibited higher frequency oscillations. This observation suggested that NARX can achieve better vibration suppression with less aggressive control actions.

Figure 8 presents the time variation of the PZT modal force, Fc, for both the NARX and PD control methods. The NARX method produced superior results compared to the PD control, which exhibited higher frequency oscillations. This observation suggested that NARX can achieve better vibration suppression with less aggressive control actions.

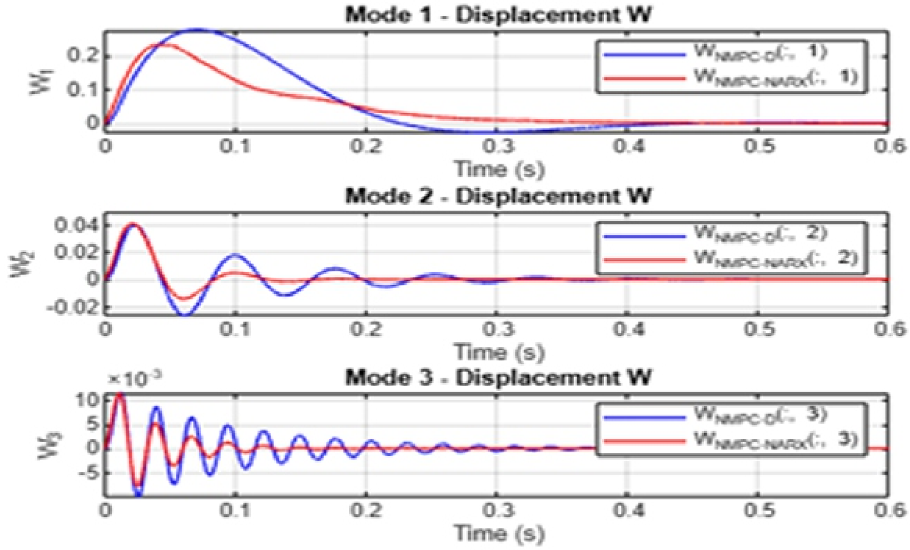

Figure 7. Comparison of Modal Time Coefficient Functions for NMPC and PD control methods

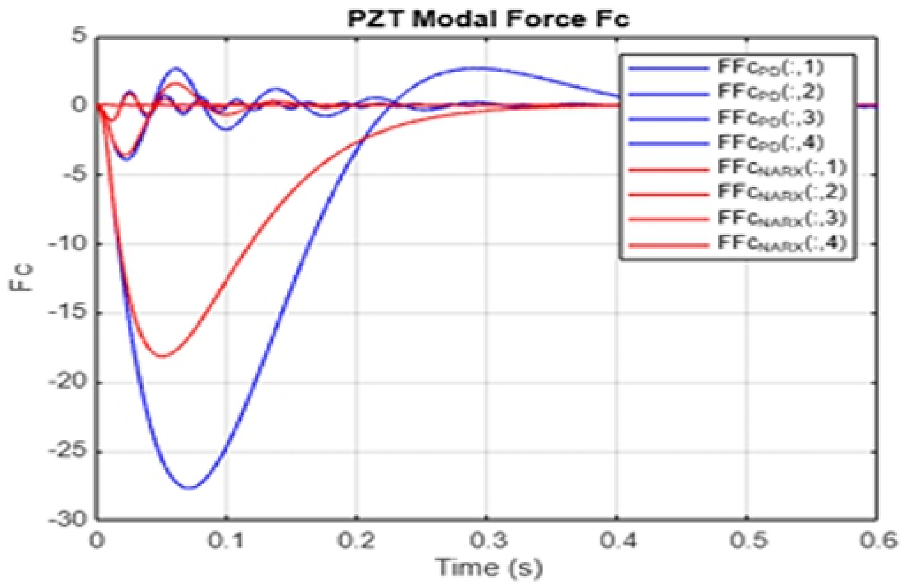

Figure 8 Time variation of PZT Modal Force Fc under NMPC and PD control

6. Conclusion

This study introduced a novel approach to vibration control of satellite beam antennas utilizing Piezoelectric (PZT) sensors and actuators integrated with Nonlinear Model Predictive Control (NMPC) and NARX control techniques. By developing a structural dynamics model tailored for flexible beam-type antennas, this study provided a robust framework for understanding and managing the complex interactions between satellite attitude and structural vibrations.

The NMPC method effectively predicted future system behaviors and optimized control actions, demonstrating its capability for precise and robust control of flexible structures. The NARXbased control, augmented with a neural network discriminator (NND), exhibited superior adaptability to dynamic environments and system parameter variations, addressing a key limitation of traditional model-based control. This continuous refinement of the NARX model ensured high performance and precision even under unpredictable conditions, making it particularly well-suited for spacecraft and robotic applications.

The NARX-based control approach demonstrated its capability to capture and manage intricate, nonlinear dynamics effectively, offering a compelling alternative to conventional control techniques that typically require explicit mathematical modeling. Its successful application in simulations underscored its potential for enhancing the stability and performance of satellite systems.

Key challenges encountered in developing real-time vibration control systems included accurately modeling the dynamic response of large elastic structures, managing nonlinearities and uncertainties, and ensuring computational efficiency within the limited resources of a spacecraft. The integration of sensors and actuators for precise data collection and effective control also proved crucial. Addressing these challenges remains essential for advancing the field and ensuring the robustness of control systems in the harsh environment of space.

This research underscored the potential of integrating advanced control strategies with smart materials to improve the performance and stability of flexible satellite structures. The findings highlighted the potential of combining NMPC and NARX techniques with PZT actuators to significantly improve satellite stability and performance. This work contributed to the advancement of space technology by providing effective solutions for controlling flexible satellite appendages, a critical aspect for future space missions.

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Evaluate the Effectiveness of Scientific Research Activities Based on Intercultural Education Theory for Social Sciences at Local Public

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ABSTRACT

The role of scientific and technological activities in the function of scientific research is one of the activities that show the role and capacity of officials and employees at universities. Intercultural education theory is an appropriate theory that refers to skills and understanding respecting different values, emphasizing integration in the context of university autonomy, including the model of local universities with their own characteristics and characteristics in organizational culture as well as development orientation in scientific research activities. The article presents theories on scientific research activities, evaluation of scientific research activities with specific cases at a local university in Hanoi on that basis, proposing the factors to build a system of criteria to evaluate scientific research activities for the social sciences at the local university.

Keywords: Scientific research activities, intercultural education, local public universities

1. INTRODUCTION

At universities today, scientific research is often encouraged and implemented in the form of applied research in addition to other potential types of research, namely development research (R&D) and basic research. Applied research activities in the fields of science, especially social sciences, are activities that require interaction and connection between research results as well as the quality of effectiveness of scientific products attached to research results of scientific research activities. Intercultural education is a term that refers to the integration and expansion aimed at finding different cultural values of each community and each region, besides these differences are considered, respected and studied from the perspective of the field of social sciences.

The use of intercultural education theory aims to determine the degree of diversity for a social institution in the relationship between individuals in a social community associated with a context and phenomenon. In the field of social sciences and humanities, the diversity of social contexts affecting the methods and results of a particular study requires a method of evaluating the effectiveness of activities for that research to solve the urgent problems needed by social science research results.

Intercultural education sets the context of the university today which is not only within the framework of the organizational culture of the university but also the development of the university for the function associated with activities and society. The link between continuing education and university performance assessment is the relevance of the University's operationalobjectives to social efficiency, specifically, the results of scientific research in the field of social sciences are considered effective if the research results of these fields come from the requirements and desire to solve outstanding problems in society.

A local public university is a special type of university that expresses the cultural characteristics of each locality and is under the management of the People's Committee of a specific province/city. Local public universities have their own cultural characteristics that distinguish them from other universities due to their local colors as well as having the same responsibilities as other universities in training quality human resources as well as being responsible for local issues. Therefore, the evaluation of the effectiveness of scientific research activities of local universities should be studied based on the theory of local cultural separation to optimize the effectiveness of scientific research activities of local universities in accordance with the context of society in the context of the autonomous development of universities.

2. Research results

2.1. Overview of scientific research and evaluation of the effectiveness of scientific research activities in the field of social sciences.

Scientific research activities are one of the functions that express the movement and development of society as well as contribute to promoting and providing answers to the nature of a thing or phenomenon in society. The understanding of the nature of things and phenomena contributes to the product of scientific research results, which is the knowledge system that answers the questions of things and phenomena

Author (Auger. P, 1961) gave the definition of the scientific phrase, this definition was used by UNESCO and became the definition used to give the nature of scientific research activities "Science is understood as the knowledge system of all kinds of laws of matter and the movement of matter, the laws of nature, society, thinking". From this definition, it can be seen that the product of scientific research here is the knowledge system, which is the foundation for the results of scientific research to be used to impact the community and society. This knowledge system is used to solve the problem of the nature of things and phenomena formed and developed by humans, this is a similar characteristic between scientific research activities and cultural factors created and used by human subjects in the community and society.

Science is an activity associated with the formation and development of society, from which it can be seen that the formation and development of this scientific field is an inevitable and objective condition that requires a science of social movement and development.Author Rick Zostak (2024) has classified in social sciences as well as the definition of the phrase social sciences “Social sciences are the fields of social sciences related to human society and human relationships with each other. These relationships are in the totality of environmental factors, which sets the nature of the connection between the social sciences and the humanities. “The essence of the phrase "society" under the approach of a science is a scientific research on the developmental fields of society, understanding the nature of interaction and relationships in a given social community. One of the factors formed in the human-owned social community along with the difference of this factor of each community or each country is the cultural factor. Cultural factors are different in nature, but in the integration and exchange of human activities, it can lead to the linkage between similar factors and values.

The definition of scientific research activities is also understood and presented in the form of the results of this activity, which is a knowledge system with its own characteristics, which is a scientific knowledge system (The National Council directs the compilation of the Vietnam Encyclopedia, 2011).

From the definition of the terms "science" and "social science", it can be seen that the nature of scientific research activities is an activity associated with the community and society, this activity contributes to the search and takes on the characteristics of "novelty" due to the human being as the subject. For scientific research activities, novelty is reflected in the use of research methods to evaluate or propose solutions to solve research objectives and impact on research subjects in society.

Regarding the definition of "scientific research activities", it is a research activity with specific research methods with the object of research being a phenomenon and the evidences of scientific research activities in the form of references, data, and knowledge that are completed through a specific research method to detect the nature of a field, specifically the field in society on that basis, providing solutions to develop and improve the effectiveness of the research problem. On the basis of scientific and social science perspectives, scientific research can provide a definition used as a basis for scientific research activities in the field of social science that is "Scientific research in the field of social science based on exploration and discovery activities with the goal of researching the nature of things and phenomena existing in society, on that basis to propose solutions to affect things and phenomena for the purpose of human and social activities".

On the basis of determining the definition of scientific research activities in the field of social sciences in order to be able to determine the effectiveness of this activity, it is necessary to have an evaluation function for scientific research activities. Evaluation activities contribute to determining the effectiveness of scientific research activities, the evaluation should be based on the results of scientific research activities as well as on the basis of what changes or impacts such research results have on the community and society.

The author (Vu Cao Dam, 2011) has given a definition of evaluation activity that is the consideration and comparison of the quantity and quality of one thing compared to another thing chosen as a standard. The standards here are the requirements for a scientific research topic including the quality of research and the accompanying products of research in a scientific field. This is an appropriate definition for scientific research evaluation activities, this definition has similarities to the assessment of scientific and technological activities in the United States, which is the use of criteria related to scientific and technological activities as a standard for scientific research activities, these criteria include: product quality, research time, financial resources for activities, and research results achieved. The evaluation method here is the use of a specific comparison method that uses the results of scientific research to compare with the existing situation in the previous society for the field of social sciences to evaluate the effectiveness of research results in the field of social sciences.

The author (Vu Cao Dam, 2008) has given a quantitative definition of the evaluation activity that is the effectiveness of scientific research is the benefit obtained after applying the results of scientific research.

Thus, it can be seen that for the scientific field, including social sciences, the evaluation of the effectiveness is reflected in whether the research ensures the conditions of research results and research products and is approved by the Professional Council. On that basis, the evaluation of scientific research results is approved with the objectives of research approved at the final level. The effectiveness of scientific research activities is reflected in the fact that such research is specifically applied to an activity of the community and society to bring about specific effects in the field of economy, environment and efficiency to society before the research results are used.

2.2. Overview of the theory of intercultural education and the application of intercultural education theory to the evaluation of the effectiveness of scientific research activities

Intercultural is a phrase defined based on the definitions of culture as well as the meaning of related words in expressing the interconnected nature of culture as products of human communities in cultural and social life. The trend of globalization has the effect of increasing relationships with communities and societies, contributing to the formation of cultural exchanges. This is a specific condition for conducting cultural exchanges between communities of people in regions, countries and territories. This is a circumstantial factor that plays a decisive role in forming theories of intercultural studies. Interculturalism is approached and studied based on studies in the field of philosophy and studies in the field of cultural studies.

The author (Huyndok.C, 2013) in the article Intercultural Philosophy, the content of the scientific article on philosophy has shown the nature of interculturalism here is the relationship and cultural exchange between different cultures. The most important feature of the inter-cultural phrase is that cultures are equal and equal among different cultures in the community or in the world. From this definition, it can be seen that intercultural is the communication between cultures on which to seek cooperation in applying the appropriate characteristics of each culture to jointly develop the community and society.

Author Nicolas Journet (2011) in the study of interculturalism under the approach of culturology stated that the nature and context of the formation of interculturalism is the context of globalization and the time of formation of intercultural definition was in the 60s and 70s of the twentieth century.

From the above two definitions based on philosophy and the cultural field, it can be affirmed that from the context of globalization to the present time when the Fourth Industrial Revolution with scientific achievements and the development of technology at the highest level, the current trend of scientific and technological activities is the trend of exchange and cooperation between countries and regions in a specific field.

Intercultural education is the formation and application of appropriate perspectives in educational activities of a particular level of education of countries with applicable and appropriate similarities to improve operational efficiency or a function in the field of education and training. The application of intercultural education theory in evaluating the effectiveness of scientific research activities, especially in the field of social sciences, is the promotion of the process of applying and using appropriate assessment experiences and criteria of countries around the world, especially the experience of evaluating scientific research activities with higher education institutions. The core values of intercultural education are the development of understanding and skills to respect differences, which is very important for scientific research.

On that basis, the application of intercultural theory in evaluating the effectiveness of scientific research is the study of the evaluation experience of countries with cultural similarities with Vietnam to find and apply the criteria for evaluating scientific research activities effectively and in accordance with organizational cultural factors at a specific organization. The university, in which the local university has the appropriate features to use intercultural theory with common and distinct characteristics about the organizational culture that influences and impacts scientific research activities.

2.3. Organizational culture from the perspective of intercultural education and impacts on scientific research activities at local public universities

A local university is a term defined based on the nature of the operation of multidisciplinary public universities under the management of the Provincial/Municipal People's Committee. The difference between a public university and a local university is reflected in two characteristics of management and operational function (Education Law 2019). From there, it can be seen that the organizational culture of the local university is also influenced by intercultural factors. Firstly, for a local university that is a public non-business unit under local management, the university will be influenced by the development orientation of the locality as well as have its own cultural features of a specific locality in the operation of the university. For example, in science and technology activities, local universities will focus and conduct scientific research to make arguments to solve local problems.

Secondly, besides the traditional culture of the locality, local universities are also influenced by intercultural factors, which are the impact trends of the world such as the context of the fourth industrial revolution, the trend of university autonomy. Therefore, it is possible to accept universities that are also influenced by organizational culture as well as new influencing factors. This trend also affects scientific research activities at local universities, which is the shift in applied research at local universities based on the strengths of the Universities.

Thus, for local universities, the development and development of intercultural theory in a specific activity plays an important role, this theory can be used to build and specific assessment criteria for this activity at local universities. Evaluation of scientific research activities at local universities will be based on the criteria of meeting the standards as prescribed, along with the application of this theory to develop and perfect the specific quantitative criteria for local universities. Within the scope of the research, the criteria for evaluation of scientific research activities for the field of social sciences will be completed at Hanoi Metropolitan University, a local university under the management of Hanoi City.

2.4. Evaluation of scientific research activities in the field of social sciences at local public universities

With the research method, it is the study of documents and observation of scientific and technological activities at the local public university. The scope of research of that article is research at the only local public university in Hanoi, which is Hanoi Metropolitan University.
Hanoi Metropolitan University is a public training institution, upgraded on the basis of Hanoi College of Education, established on January 6, 1959. Hanoi Metropolitan University was established under Decision No. 2402/QD-TTg dated December 31, 2014 of the Prime Minister, under the People's Committee of Hanoi, under the State management of education of the Ministry of Education and Training. Over the past 8 years of construction and development, the University has increasingly affirmed its position in the university system of Vietnam, as well as its role and position in the socio-economic development of Hanoi City. Scientific research activities are one of the three important functions of Hanoi Metropolitan University. In the orientation of important research areas of Hanoi Metropolitan University, the field of social sciences and the field of educational sciences play an important role, these are two areas of research associated with applied tasks, associated with the

requirements of training high-quality human resources associated with the requirements and tasks of Hanoi City.

Hanoi Metropolitan University (2024) in the Preliminary Evaluation Report on the Implementation of the Law on Higher Education in the period of 2019 – 2023, the report assessed the results of achievements in scientific research activities of Hanoi Metropolitan University. The number of scientific research projects of the University as well as scientific products of the University's staff and employees.

Table 1. Statistics of the number of scientific research topics period 2019 – 2023

Year	**Classification of the topic**			**Total**
	Public	**Ministry Level**	**Grassroots level**	
2019	02	03	50	***58***
2020	01	01	46	***49***
2021	01	01	46	***48***
2022	00	01	41	***42***
2023	00	00	34	***34***
Total	***05***	***06***	***217***	**239**

[Source: Hanoi Metropolitan University (2024) in the Preliminary Assessment Report on the Implementation of the Law on Higher Education in the period of 2019 – 2023].

From the above data table, it can be seen that the development efficiency of scientific research activities at Hanoi Metropolitan University through the number of topics is a clear criterion for evaluating the level of development.

The total number of topics according to the statistical method out of 239 approved topics of the University in the period from 2019 to 2023, the number of topics in the social field is 120 topics with a rate of 50%. This is suitable for the field of strengths of Hanoi Metropolitan University with the starting point being a university with a tradition of training in pedagogical human resources as well as social sciences, so the scientific and technological human resources are mainly in the field of social sciences.

This is a factor related to organizational culture to be able to identify and evaluate the effectiveness of scientific and technological activities. Based on the factors related to the organizational culture of the University developed from the training of the pedagogical and social sciences, the evaluation of the effectiveness of scientific and technological activities in the scientific field based on the intercultural approach should be based on the assessment according to the roadmap from the development of the breadth based on quantity and the development of the depth based on quality. This is appropriate because through the development stage of a local university from a college level to a multidisciplinary university, there are changes in the formation and construction of research and implementation skills for a scientific research topic, from which the use of topics to improve research skills for the staff and employees of the University is appropriate. In addition, when the research skills of the staff and employees have developed, it is reflected in the participation in scientific research tasks at many levels along withthe field of social sciences as well as determining the applicability of scientific research topics in order to meet the requirements of solving social problems as well as the requirements of improving the quality of the university's operations, which requires funding resources for scientific research activities and the quality of scientific research products. This leads to a reduction in the number of university-level research projects in a lower number, but the qualityand product requirements for scientific research activities as well as funding for activities will also be provided at a higher level with more resources to form a level of quality in evaluating the effectiveness of scientific research activities. The formation and change in organizational culture for the evaluation of the effectiveness of scientific research projects, especially the evaluation of the effectiveness of scientific research activities in the field of social sciences according to the quality of products in scientific research and the feasibility and application of research results, is appropriate to demonstrate the change in the approach to building organizational culture, as well as the application of views on intercultural education in evaluating the effectiveness of scientific research activities at Hanoi Metropolitan University.

The evaluation of the effectiveness of scientific research activities at Hanoi Metropolitan University can also be considered and evaluated based on the quality and quantity of scientific research products of the University's staff and employees.

Table 2. Statistics of the number of scientific research works in the period of 2019 – 2023

Year	There are scientific research works				
	WoS	Scopus	aci	International Journal of Sciences:	National scientific journals
2019	6	4	0	6	61
2020	12	2	0	15	49
2021	12	7	0	10	67
2022	4	4	1	20	80
2023	9	5	1	15	88
Total	43	22	2	66	345

[Source: Hanoi Metropolitan University (2024) in the Preliminary Assessment Report on the Implementation of the Law on Higher Education in the period of 2019 – 2023].

From the above data table, it can be seen that the number of scientific research works of Hanoi Metropolitan University has developed, which is consistent with the development orientation and culture of the University, which is the research in the field of social sciences associated with the application orientation. Of the total number of scientific research works, the statistical method used to evaluate the proportion of scientific research works has similarities with the number of scientific research projects.

The habitual and cultural characteristics of research in the field of social sciences are that often the works that will be studied are directed to domestic scientific journals, which is also relevant to the field of research. However, in the trend of intercultural education, the need to have criteria to evaluate the effectiveness of scientific research activities based on scientific research works at the international level is consistent with the development trend. For the intercultural approach inthe field of social sciences, the cultural change in scientific research activities based on the number of international research works in his field will contribute to the development of the University's research team, reflected in the improvement of qualifications through higher level learning activities of employees and more experts in the field of research to form strong research groups.

Table 3. Statistics of the number of books and textbooks in the period 2019 – 2023

No.	Year	Total	Published books and textbooks			
			Monographs	REFERENCE	Syllabus	Others
1	2019	24	5	2	17	0
2	2020	103	8	7	9	79
3	2021	137	4	8	24	101
4	2022	13	0	0	13	0
5	2023	22	0	0	22	0
Total			**17**	**17**	**85**	**180**

[Source: Hanoi Metropolitan University (2024) in the Preliminary Assessment Report on the Implementation of the Law on Higher Education in the period of 2019 – 2023].

Books and textbooks are also one of the products of the scientific research process. Currently, the evaluation of whether a syllabus is effective or not is the same as a scientific research project, which depends on the opinion of the Professional Council to decide whether the syllabus is eligible for acceptance or not to be accepted, thereby serving as a basis for the publication and use of the syllabus. The number of syllabus published in 2023 has a sharp decrease with 22 syllabus published down 5 times compared to 137 syllabus published in 2023. This shows the quality and effectiveness of the syllabuses that need to be reviewed and evaluated to improve the effectiveness of scientific materials to meet the needs of the training disciplines, including the training disciplines in the field of social sciences of the University.

Thus, for the evaluation of scientific research activities in the field of social sciences at Hanoi Metropolitan University, there are characteristics consistent with the theory of performance assessment on scientific research activities as well as the theory of intercultural education leading to changes in scientific research activities. The completion of the evaluation of the effectiveness of scientific research activities in the field of social sciences at local universities, including Hanoi Metropolitan University, should use intercultural education theory as well as theories on evaluating the effectiveness of scientific research activities to overcome the shortcomings in scientific research activities in the context of interculturalism and the impact of the inevitable trend of university autonomy in accordance with the development orientation of education and training activities.

Firstly, it is necessary to determine the effectiveness of researches in the field of social sciences associated with the University's application orientation that this research objective is financially effective, this evaluation to optimize the funding resources for scientific and technological activities is

still limited at local universities such as Hanoi Metropolitan University.
Second, intercultural approach is associated with the effectiveness of scientific and technological activities on the values brought to the community and society.

Thirdly, the approach to intercultural education requires effective scientific and technological activities that affect other areas of the university's operations without requiring criteria to evaluate the effectiveness between training and scientific research activities.

2.5 Proposing some criteria for evaluating the effectiveness of scientific research activities in the field of social sciences at local universities

The evaluation of the effectiveness of scientific and technological activities at local universities, including Hanoi Metropolitan University, is appropriate, but it is necessary to have more criteria to evaluate the coordination between the effectiveness of scientific and technological activities with the resources and fields of activities of the university in addition to the completion of the results of scientific research activities.

Firstly, perfecting the criteria of financial efficiency for the field of social sciences is the effectiveness of the research results in the field of social sciences, which clarifies the benefits of the research results and the approved costs for scientific research topics. Quantitative criteria can be used to evaluate the efficiency that is the determination of economic efficiency by the calculation formula including:

Financial efficiency = Total financial value to be obtained - Total cost for scientific research projects.

For the field of social sciences, the determination of the obtained financial value can also use a number of qualitative criteria such as: Social impact on the research results of the topic; New scientific arguments from the research results of the topic.

In some research projects in the field of social sciences, qualitative criteria need to be evaluated for a long time after the research results are accepted and published, the evaluation of the effectiveness of scientific research activities in the field of social sciences can be further used. other efficiency evaluation criteria close to the field of research such as social efficiency for research in the field of social sciences. The evaluation of financial efficiency can solve the problem of having financial resources with more invested financial resources to promote scientific research products that are more quality and quantity works, articles or textbooks.

Secondly, the effectiveness criterion for society, this is an important criterion for the evaluation of effectiveness in the field of social sciences, the field of society is the object of research of the social sciences major. The current theory of intercultural education is a theory that expands the scope and impact of a topic from the perspective of the impact of intercultural factors. Evaluation of the effect on society can be applied in the evaluation of scientific research in the field of social sciences. Intercultural education theory can be applied in evaluating the effectiveness of scientific research in the field of social sciences as well as scientific and technological products, textbooks in this field are the skills of the research team in solving the problems of society through research results. The effectiveness of scientific research activities is to promote the solution of social problems, this is the first criterion to evaluate the effectiveness of a research activity in the field of social sciences.

For example, the use of quantitative criteria in research objectives for scientific research activities in the field of social sciences is also an interdisciplinary approach to evaluate the effectiveness and clarify the "novelty" of scientific and technological activities.

Thirdly, the effectiveness criteria in the field of training, the effectiveness criteria in the field of training show the role of scientific and technological activities on training activities contributing to the operation of the University. Criteria for evaluating the effectiveness of scientific research activities in the field of training related to the quality of human resources. In the field of social sciences, intercultural education theory provides skills for each individual. This applies to evaluating the effectiveness of activities to improve the quality of human resources in evaluating the effectiveness of scientific research activities reflected in research skills and the development of research skills for scientific research activities. Criteria for evaluating the effectiveness of scientific research activities in the field of training for universities are reflected in the fact that the textbooks and monographs of the field of social sciences have a role and influence on the major of training, on that basis, it is possible to determine the role of influence, effectiveness and necessity of the textbooks associated with the field of training of the University, which initially contributes to solving the situation of the number of textbooks and monographs in a modest number of local universities.

effectiveness of financial efficiency for society and the effectiveness of training activities are the criteria frameworks that are determined to be able to research and supplement to become the criteria for evaluating the effectiveness of scientific research activities in the field of social sciences in the context of university autonomy in the current context.

3. Conclusion:

Scientific research activities in the field of social sciences are characterized by factors affecting economic and social efficiency and training activities in the field of social sciences. The use of theories on the evaluation of the effectiveness of scientific research activities using educational intercultural theory as well as the development of performance assessment criteria is feasible, contributing to the identification of appropriate factors to be able to develop criteria for evaluating the effectiveness of scientific research activities for local universities, including the initial research to propose criteria for evaluating the effectiveness of scientific research activities in the field of social sciences at universities.

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Theoretical and Experimental Considerations Regarding the Evaluation of the Mechanical Characteristics of Polyethylene Pipes Under Multiple Loading Conditions

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A B S T R A C T

Polyethylene pipes are used in most applications for the transport and distribution of drinking water. Pipe systems generally have complex routes that include undercrossings of roads. Consequently, the pipe loads are complex, resulting from: internal fluid pressure, soil loads, traffic pressure. In a test program aimed at evaluating both the axial stress behavior and the mechanical characteristics of polyethylene pipes used in the construction of water distribution piping systems, in the presence of defects, theoretical and experimental research was carried out. The main scope of the research carried out was to determine the behavior of PE100 polyethylene pipes under multiple stress conditions. Thus, a PE100 polyethylene pipe was successively analyzed in analytical evaluation, traffic overpressure simulation, internal pressure test and numerical evaluation. The purpose of performing the multiple stress test of the buried Pe100 polyethylene pipe was to evaluate the influence of a defect that can occur on the outer surface of the pipe during installation in the trench, by simulating localized traffic overload and internal pressure, and determining the stress intensity factor, KI. The present work represents a novelty and it is the main contribution in the buried PE pipe mechanical behavior field. The study addresses how the shape, position, and size of the surface defect could affect the value of the stress intensity factor. By modifying the values of the geometric dimensions of the defect, obtained by imprinting on the outer surface of the pipe with outer diameter, De = 90 mm, wall thickness, s = 5.4 mm, and a length, Lpipe = 4000 mm, the viscoplastic character of the material was highlighted. The calculated value of stress intensity factor, KI, is 0.7007 MPa·m1/2, and calculated value of the maximum stress is 19.654 MPa. By numerical evaluation, the value of maximum stress developed in the pipe wall was obtained as 19.937 Mpa.

Keywords: polyethylene pipe, defect, stress, strain, stress intensity factor, traffic

1. INTRODUCTION

1.1 Theoretical considerations regarding the evaluation of the mechanical characteristics of polyethylene pipes under multiple loading conditions

Distribution networks are relatively difficult to operate because they are long, in some segments they are positioned under the road and operate at continuously variable technological parameters (BICA I., 2013).

The mechanical behavior of PE100 polyethylene can be assessed through a basic characteristic, called toughness. Toughness is the ability of a material to withstand large plastic deformations under the action of a high level of loading until it breaks.

In order for the presence of a physical defect not to cause the destruction (rupture) of a resistance element, it is necessary that the value of the toughness characteristic, determined analytically for that defect, be lower than a critical value of the toughness characteristic, called fracture toughness (BRÎNZAN O., 2006).

In the specialized literature, two seemingly similar notions are used, but with different areas of applicability, namely:
a) the toughness of materials specific to materials considered without physical discontinuities (voids, cracks, etc.) and generally assessed based on the surface area under the characteristic tensile curve;
b) the fracture toughness of materials specified for materials (strength elements) that present physical discontinuities (voids, cracks, etc.)
The British standard (EN 1295-1, 1998), through its two component parts, namely: Part 1: General requirements and Part 2: Summary of nationally established design methods, is the normative framework necessary for conducting experimental testing to evaluate the mechanical characteristics of polyethylene pipes under multiple loading conditions.

This standard provides information on the structural design of buried pipelines under various loading conditions. Also, (EN 1295-1, 1998) contains calculation recommendations regarding the stresses and deformations obtained from simultaneous loading. In (EN 1295-1, 1998) there are specifications regarding the effect of pressure on pipe deformation, on pipe buckling under pressure, as well as on longitudinal thrusts and stresses.

The correct and sustainable operation of a water supply system is determined by proper design and execution. Increased attention is currently being paid to advancing the installation of trenchless pipeline installation techniques, as well as guaranteeing their lifespan of more than 50 years.

To determine the solution for laying the pipeline pipes in the trench, the type of retaining walls and the method of filling, it is important to have a good knowledge of the soil lithology and the geotechnical characteristics of the ground.

The loads to be considered refer to:
a) permanent loads, such as ground overburden, asphalt weight (if any) and the self-weight of the pipeline;
b) variable loads, such as the uniformly distributed surface load, the vertical load caused by traffic, the weight of the transported fluid and the load from internal and external pressure, other than atmospheric.

All these loads have an effect on the operational behavior of the buried polyethylene pipe. Under certain conditions, the level of stresses developed in the pipe wall, especially in the presence of defects, can reach the limit state (MANU ID., PETRESCU MG., ZISOPOL DG., NAIM RI., ILINCA CN., 2024).

In order to prevent the rupture of pipelines in service that have defects, the allowable stress level of the pipeline, σ_{adm}, can be determined based on the critical stress intensity factor, K_{Ic}, and the dimensions of the defect(s).

The critical stress intensity factor corresponding to the mode I of propagation through the opening of the defect, KIc, is a material characteristic that is the ability of a body with a defect to resist the stresses acting around the defect and was experimentally determined in (ALUCHI, 2013), obtaining the value KIc = 0.743 MPa·m1/2.

The critical stress intensity factor, KIc, is useful in verifying the condition of non-initiation of the rupture process, given in the relation (1).

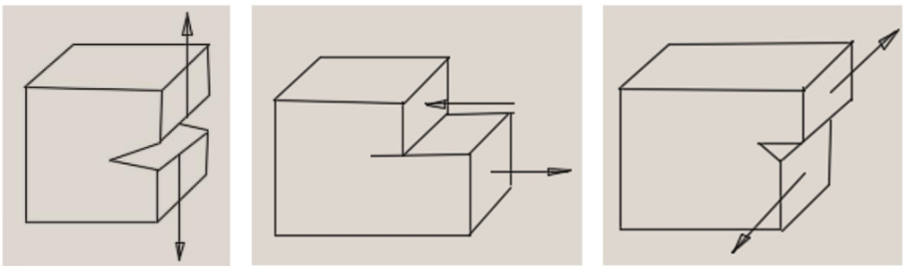
$$K_I \le K_{I_c} \qquad (1)$$

where:

KI – stress intensity factor corresponding to the mode I propagation through the defect opening, [MPa·m1/2];

KIc – critical stress intensity factor, a material's feature of the pipe, [MPa·m1/2].

According to Irwin, the edges of a defect can have three independent kinematic motion modes, highlighted in the figure 1a, 1b, and 1c.



a) b) c)

Figure 1. Independent kinematic movement modes of the edges of a defect: a) mode I or tensile opening mode; b) mode II or in-plane sliding opening mode; c) mode III or anti-plane sliding opening mode

Due to analytical difficulties, explicit solutions to the problem of defects in three-dimensional bodies include circular and elliptical defects.

The analytical expression of the stress intensity factor, KI, for the case of a pipe that presents an unpenetrated semi-elliptical defect on the external surface (figure 2), whose opening is made according to mode I, is given by relation (2).

$$K_I = \sigma_{ech}\sqrt{\pi c \beta (a, L_{pipe})} \qquad (2)$$

where:

σ_{ech} – equivalent stress, [MPa];

c – half-length of the defect, measured in the direction in which the defect extends, [mm];

β – coefficient that depends on the dimensions of the defect and the part it contains;

a – depth of the defect, [mm];

L_{pipe} – length of the pipe containing the defect, [mm].

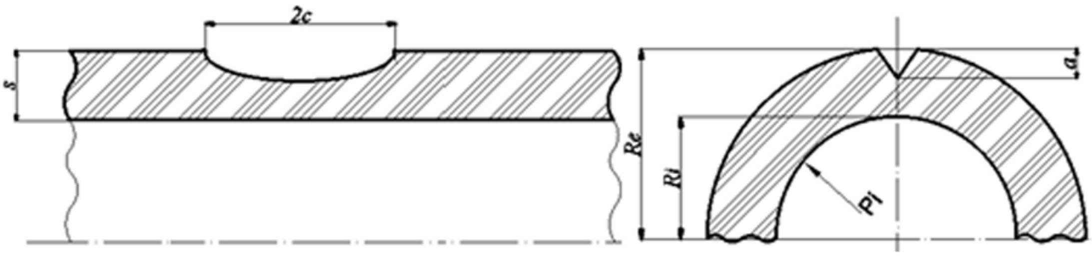


Figure 2. Section in a PE100 pipe with unpenetrated semi-elliptical defect

To determine the value of the stress intensity factor, K_I, in the case of an unpenetrated semi-elliptical defect, shown in figure 2, at a depth $a < s$, the relation (3) is used, according to (ULMANU, V., ZECHERU Gh., 1994).

$$K_I = \left[M_F + \left(\Phi\sqrt{\frac{c}{a}} - M_F \right) \cdot \left(\frac{a}{s} \right)^8 \right] \cdot \frac{\sigma\sqrt{\pi \cdot a}}{\Phi} \cdot M_{TM} \qquad (3)$$

where:

M_F - factor that depends on the geometry of the defect (a/c), which is determined by relation (4).

$$M_F = \sqrt{1 - \left(\frac{a}{c} \right)^2} \qquad (4)$$

Φ – the complete elliptic integral of the second degree, which is determined by relation (5).

$$\Phi = \int_0^{\pi/2} \sqrt{1 - e_f^2 \cdot \sin^2 \varphi} \cdot d\varphi \qquad (5)$$

e_f – elliptic modulus or eccentricity; $e_f = \tan\varphi$

φ – defect angle; [º]; $\varphi = \cos^{-1}\left(\frac{a}{c} \right)$

M_{TM} – correction factor that takes into account the increase in stress due to radial deformation in the vicinity of the defect and which is determined with the relation (6).

$$M_{TM} = \frac{1 - \frac{a/s}{M_T}}{1 - \frac{a}{s}} \qquad (6)$$

M_T – Folias correction factor, for the ratio $\lambda < 1$, $M_T = \sqrt{1 + 1,61\lambda^2}$;

λ – ratio, $\lambda = \frac{c}{\sqrt{R_m \cdot s}}$, where c – half-length of the defect, R_m – average radius and s – wall thickness.

1.2 Experimental considerations regarding the evaluation of the mechanical characteristics of polyethylene pipes under multiple loading conditions

2. Materials and methodology

1) Materials used in the multiple stress test of buried PE100 polyethylene pipe (a) Pipe

The PE100 polyethylene pipe used for the multiple stress test (Figure 3) had the following dimensional and material characteristics: pipe outer diameter, D_e = 90 [mm]; wall thickness, s = 5.4 [mm], pipe length, L_{pipe} = 4000 [mm]; pipe material density, ρ_{PE100} = 960 [kg/m^3].

Figure 3. The PE100 polyethylene pipe used for the multiple stress test

(b) The filling material

The pipe was laid in an irregular trench, without supervision, with soil with stones or rocks for which n_2 - coefficient that takes into account the type of terrain is n_2 = 6, being unsettled terrain. The pipe bedding, made of the filling material, is shown in Figure 4a. The backfill material used in the experiment is shown in Figure 4b.

a) b)

Figure 4. Aspects of laying a PE100 polyethylene pipe in a trench:
a) pipe bedding; b) backfill material

The metal tubes, two in number, were used to simulate the load due to street traffic, P_t. Thus, the experiment used the additional load produced by the weight of the two metal tubes, shown in Figure 5, having: tube outer diameter, D_{tube} = 250 mm, tube wall thickness, s_{tube} = 11.3 mm, tube length, L_{tube} = 1840 mm, and tube material density, $\rho_{steel} = 7.85 \cdot 10^3$ [kg/m^3].

Figure 5. Metal tubes used to simulate the load due to street traffic

(c) Used equipment

In the multiple stress test of the buried PE100 polyethylene pipe, the Rems Push manual pressure test pump (Figure 6a), with a maximum pressure of 160 bar (Figure 6b), the Shangli CPCD30 diesel forklift (Figure 7) and the experimental facility used for testing of polyethylene pipes were used.

a) b)

Figure 6. The Rems Push manual pressure test pump: a) general view; b) detail

Figure 7. Shangli CPCD30 diesel forklift

2) Methodology used in the multiple stress test of buried PE100 polyethylene pipe PE100 polyethylene pipes and fittings must be buried according to (ASTM D2774, 2012) and (PE Pipe, 2006) for pressure systems.

The installation of polyethylene pipes can be carried out, according to (BAI Q., BAI Y., RUAN W., 2017) and with an open trench with/without sand bed, by the plowing method - DVGW GW 324. As a rule, the trench has a width of 50 cm + De (cm), according to (NE 035-06, 2006).
The pipe material is chosen depending on the water quality and soil aggressiveness. Corrosion resistance of the pipe material and not of the subsequent wall protection is preferred, according (NE 035-06, 2006). For this reason, the pipe made of PE100 polyethylene material was chosen.

The PE100 polyethylene pipe used in the experimental test had caps applied to ensure sealing of the ends (Figure 8). Type A steel caps were installed with threaded connections, shown in figure 9, according to ISO 1167-1.

Figure 8. Pipe with type A caps mounted at its ends

a) b)

Figure 9. Type A steel caps: a) graphic representation; b) real appearance

Subsequently, the pipe was positioned on the workbench to create a graphic representation of the marks on its surface in order to identify the exact position of the defects produced during the trench installation phase.

The distance between two consecutive circumferential marks - along the length of the pipe - was 30 mm (Figure 10a), and the distance between two consecutive horizontal marks - along the circumference of the pipe - was 40 mm (Figure 10b). Circumferential markers from 1 to 50 and horizontal markers from A to H were drawn (Figure 10c).

a) b)

c)

Figure 10. Creating a graphic representation of the marks on the surface of the Pe100 pipe: a) drawing the circumferential marks; b) drawing the horizontal marks; c) the final appearance of the graphic representation of the marks drawn on the outer surface of the Pe100 pipe

For the multiple stress testing of the polyethylene pipe, the following steps were carried out:
a) mechanized digging of the trench with length, L = 5000 mm, width, l = 600 mm and depth, h = 500 mm;
b) creation of the foundation bed, using the filling material shown in figure 11;
c) positioning the test pipe on the foundation bed;
d) connecting the pipe through the hole in one of the two covers to the Rems Push pump;
e) introducing water to obtain internal pressure;
f) overlapping metal pipes to simulate traffic overpressure;
g) identification of defects made on the outer surface of the pipe during the stressing stage;
h) analysis of the identified defects;
i) stressing the pipe to internal pressure until it bursts;
j) identification of the defect that caused the pipe to burst.
Pipe is shown in the preliminary stage of installation in the trench in the figure 11.

Figure 11. Pipe in the preliminary stage of installation in the trench

Figure 12 shows the overlapping of metal tubes over PE100 polyethylene pipe for the purpose of simulating traffic overload.

Figure 12. Applying an external load (122.3963 kg) to the defect area to simulate localized traffic overload

After performing the traffic overload simulation stage, non-destructive examination of the Pe100 polyethylene pipe was performed, carried out by visual inspection. During the visual inspection, defects of type lack of material were identified, such as imprint (figure 13a), scratch (figure 13b) and microcrack (figure 13c), positioned on the outer surface of the pipe.

a) b) c)

Figure 13. Defects of type lack of material identified on the outer surface of the PE polyethylene pipe: a) imprint, b) scratch; c) microcrack

After internal pressure testing of the pipe (figure 14), it was found that the defect identified in the form of a scratch, shown in figure 13c, was the defect that caused the pipe to burst.

Figure 14. Internal pressure testing of the pipe

The location and description of the defect are requirements in writing an experimental test report. In this regard, the defect was positioned in the GH 23-26 space (figure 15) and had the appearance of a scratch, 9 mm long and 1.2 mm deep (MANU ID. – PhD Thesis, 2024).

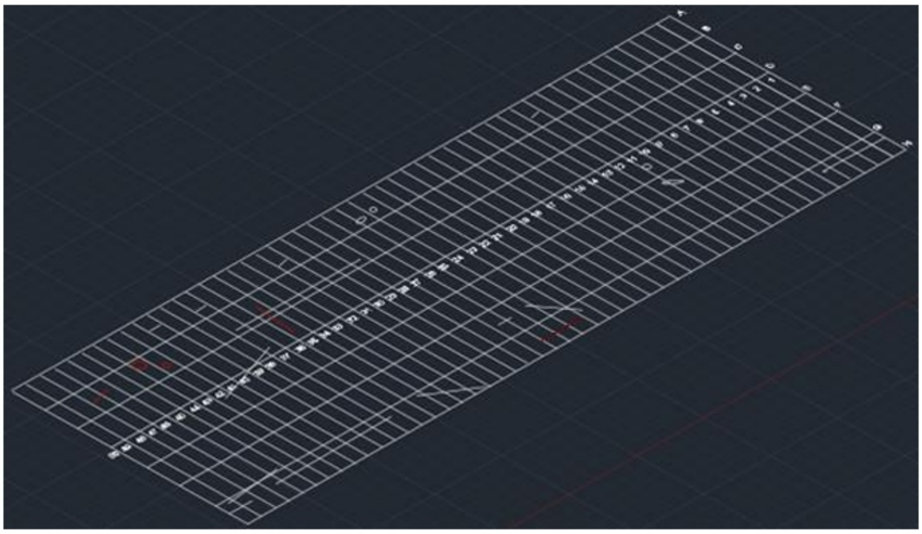


Figure 15. Positioning of defects identified on the outer surface of the PE100 polyethylene pipe after traffic overload simulation

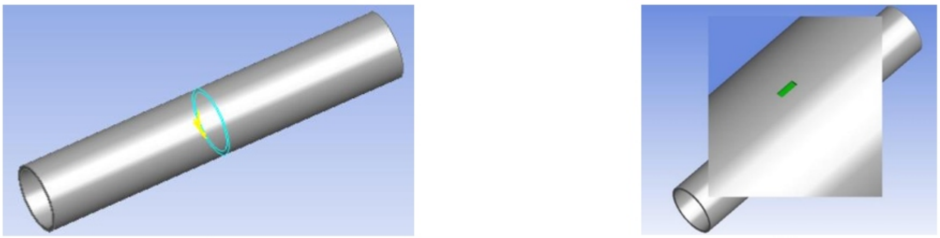
The PE100 polyethylene pipe subjected to multiple stress testing was numerically evaluated through a study conducted in the Ansys program.
The purpose of the numerical evaluation was to evaluate the influence of the identified defect on the strength of the tested pipe. For this purpose, the defect depth values were consecutively increased from 10% to 70% of the wall thickness, s. The same procedure was applied to the length of the defect, which was consecutively increased from 10% to 70% of the pipe length, Lp. For the tested pipe, in the ENGINEERING DATA stage, the same characteristics of the Pe100 polyethylene materials presented in the table 1 were used.

Table 1. Material characteristics of PE100 polyethylene

Material characteristic	Symbol	Material characteristic value	Unit of measurement
Density	ρ	960	[kg/m^3]
Young's modulus	*E*	1100	[MPa]
Poisson's ratio	μ	0.45	-

Since the structure of the pipe under analysis presents both longitudinal and transverse symmetry, in order to improve computational efficiency, a model with a length of 500 mm was adopted.

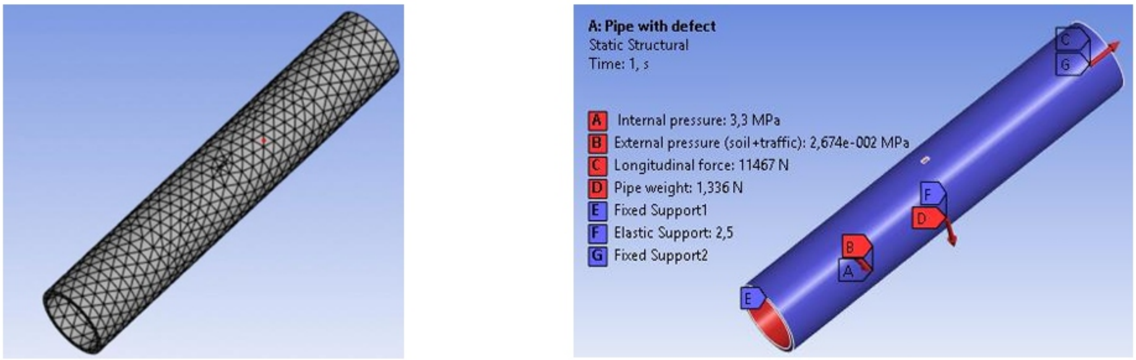
In the GEOMETRY stage, the geometry of the PE100 pipe was create (Figure 16a). The scratch type defect, 9 mm long and 1.2 mm deep, was created and its appearance is shown in the figure 16b.



a) b)

Figure 16. Geometric models: a) of the PE100 pipe; b) of the defect

In the MODEL and SETUP stages of the numerical analysis, the pipe discretization was performed and the loads acting on the pipe were introduced and positioned (figure 17).



a) b)

Figure 17. MODEL and SETUP stages of the numerical analysis:

a) the pipe discretization; b) loads acting on the pipe

3. Results

The results obtained in the evaluation of the polyethylene pipe under multiple stress conditions and their interpretation are presented in tables 2, 3 and 4 and in figures 18, 19, 20, 21, 22, 23 and 24.

For evaluating the polyethylene pipe under multiple stress conditions, for the stress intensity factor, KI, the value presented in table 2 was obtained by using the calculation relations (3), (4), (5) and (6).

Table 2. The stress intensity factor, KI, for polyethylene pipe evaluated under multiple stress conditions

Average pipe diameter	Defect depth	Defect length	Half of defect length	Average radius	Wall thickness	Report	Folias correction factor
D_m	a	L_{defect}	c	R_m	s	λ	M_T
[m]	[m]	[m]	[m]	[m]	[m]	[-]	[-]
0.0846	0.00012	0.009	0.0045	0.0423	0.0054	0.2977	1.069
	Correction factor	Defect angle	Elliptic modulus or eccentricity	Complete elliptic integral of	Factor depends on the	Maximum stress	Stress intensity factor

			the second degree	defect geometry		
M_{TM}	φ	e_f	Φ	M_F	σ	K_I
[-]	[°]	[-]	[-]	[-]	[MPa]	[MPa·m$^{1/2}$]
1.0184	1.0366	1.6906	1.6904	0.9638	19.654	0.7007

During the traffic overload simulation phase, defects such as imprints, scratches and microcracks were observed on the external surface of the pipe. The scratch defect, 9 mm long and 1.2 mm deep (representing 22.22% of the pipe wall thickness), was the cause of the pipe bursting.
The polyethylene pipe bursting occurred through local swelling around the defect identified as being located in the GH 23-26 space, concomitant with wall thinning until failure (Figure 18). The length of the portion of the pipe affected by the rupture was 35 mm.

Figure 18. PE100 polyethylene pipe failure evaluated under multiple stress conditions

The burst pressure values and burst time values recorded for the PE100 polyethylene pipe evaluated under multiple stress conditions are presented under the pressure-time (bar-s) diagram, shown in Figure 19 and Table 3.

Figure 19. Pressure-time diagram (bar – s) for PE100 polyethylene pipe evaluated under internal pressure test stage

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Table 3. Results recorded to testing PE100 pipe evaluated under internal pressure test stage

Testing pipe	Burst pressure	Burst time
	P_i, [bar]	t, [s]
PE100 polyethylene pipe evaluated under multiple stress conditions	33	149

To study the behavior of the PE100 polyethylene pipe evaluated under multiple stress conditions, the following diagrams were drawn: internal pressure - time, hoop stress - internal pressure, hoop stress - hoop deformation and axial stress - internal pressure (Figure 20).

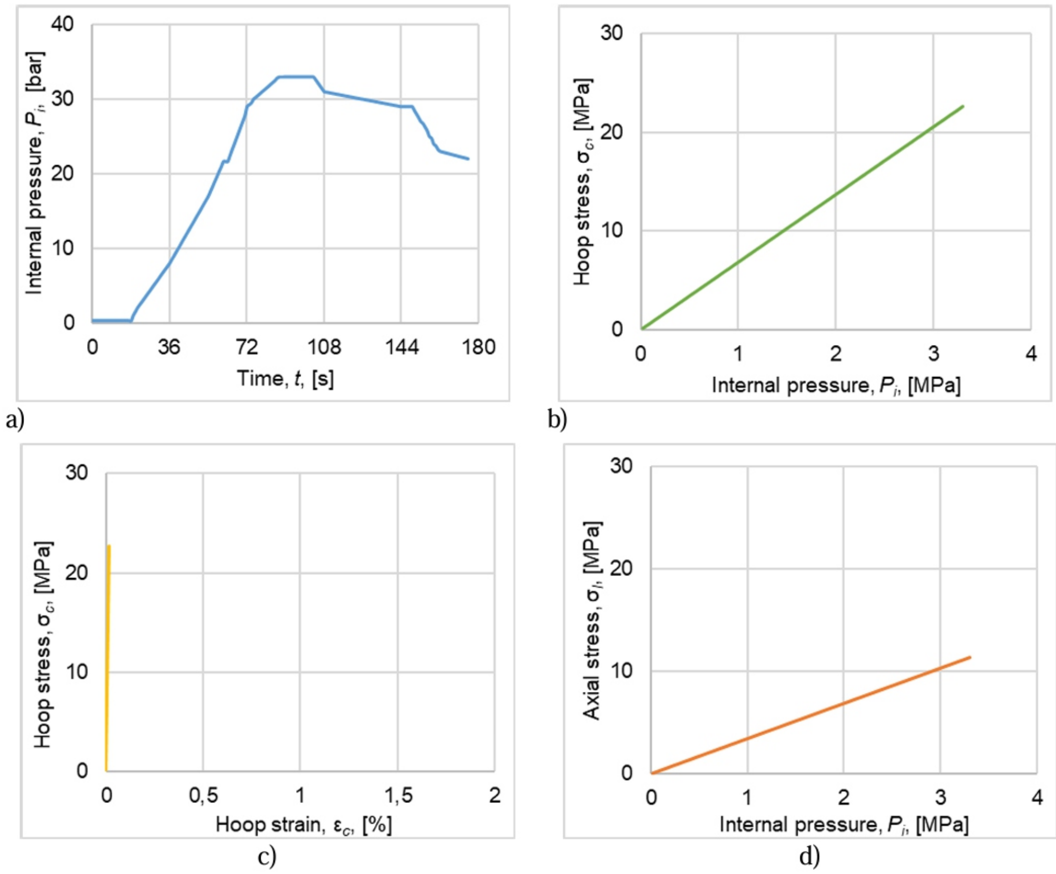

Figure 20. Diagrams for PE100 polyethylene pipe evaluated under internal pressure test stage: a) $P_i - t$; b) $\sigma_c - P_i$; c) $\sigma_c - \varepsilon_c$; d) $\sigma_l - P_i$

In the numerical analysis, in the SOLUTION stage, results were obtained in the form of stresses, strains and equivalent stresses, presented in Figure 21.

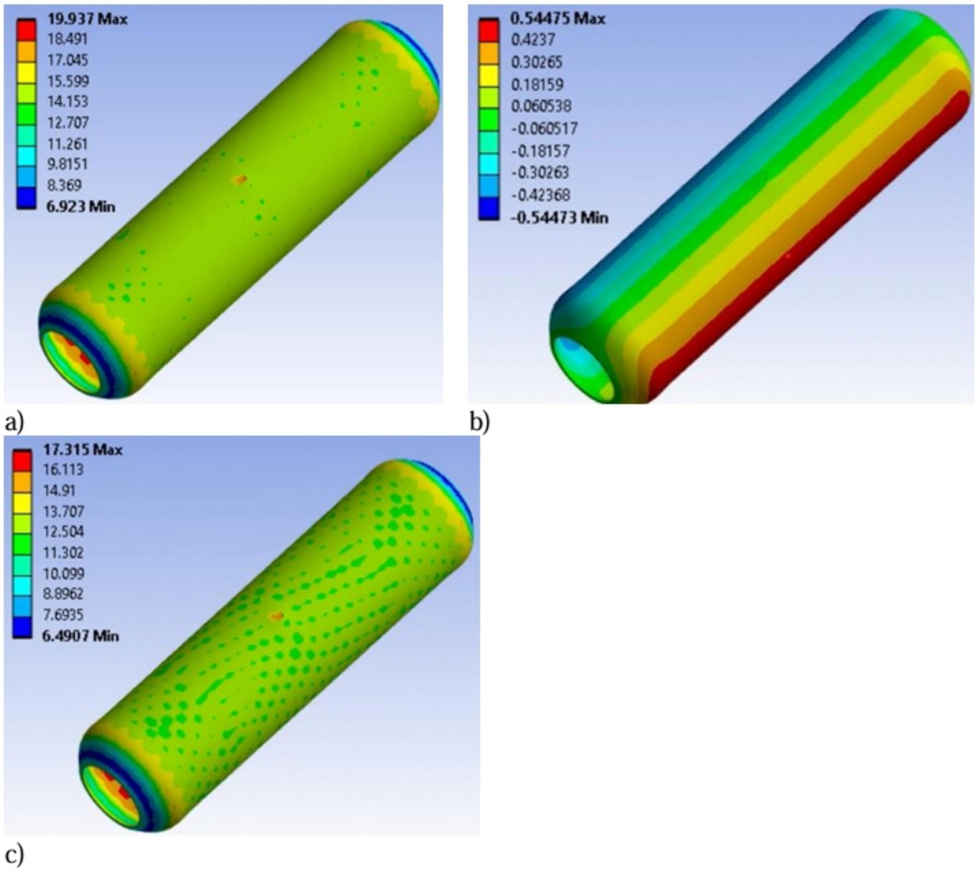

Figure 21. Results obtained in SOLUTION stage of numerical analysis: a) strength values; b) strains values; c) equivalent stress values

To present the maximum values of the Stress Intensity, Equivalent Stress, Directional Deformation parameters and analyze the influence of defects on the mechanical strength of the PE100 pipe, printscreens are shown with the modified values of the defect depth, a, (Figure 22), and with the modified values of the defect length, 2c, (Figure 23) and, implicitly, the modified values of the Stress Intensity parameter.

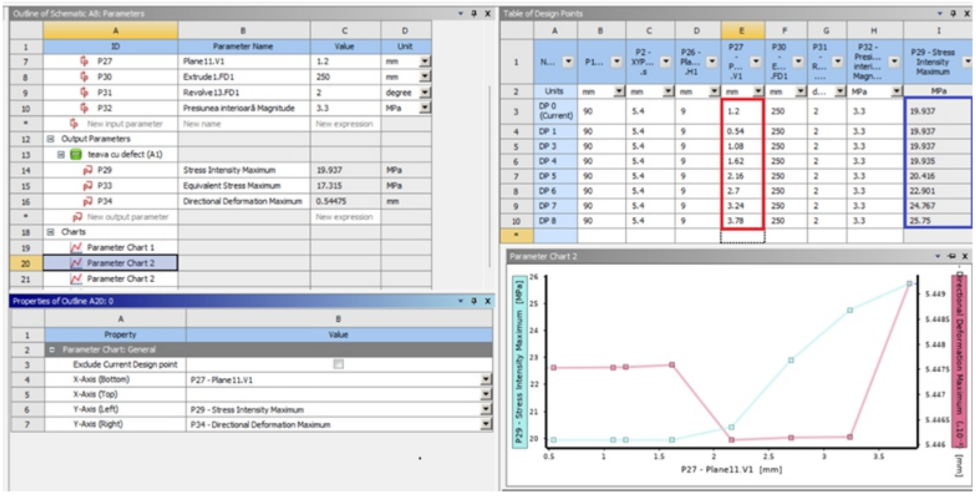

Figure 22. Parameter analysis - change in defect depth

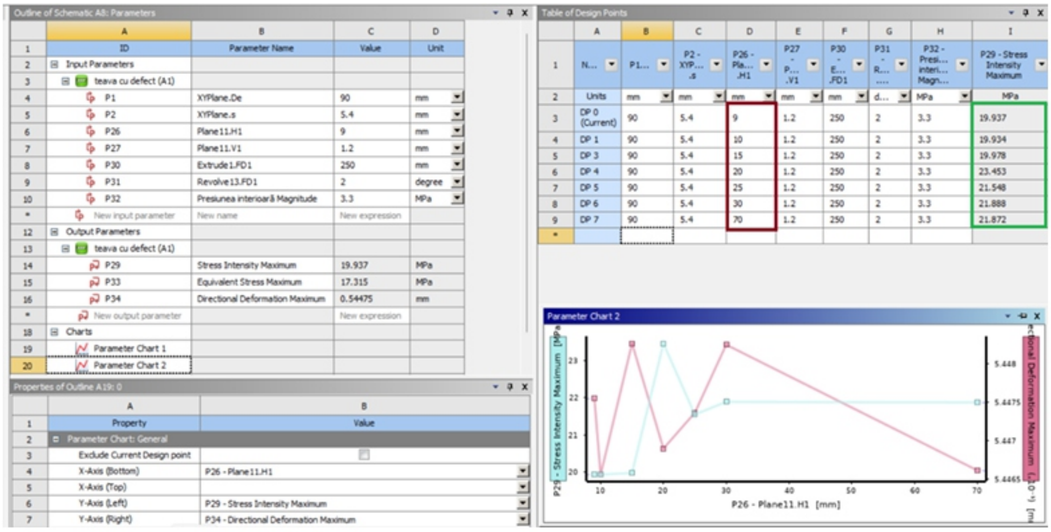

Figure 23. Parameter analysis - change in defect length

Also, the influence of the geometric dimensions of the defect on the strength of the Pe100 polyethylene pipe evaluated under multiple stress conditions is shown in Figure 24.

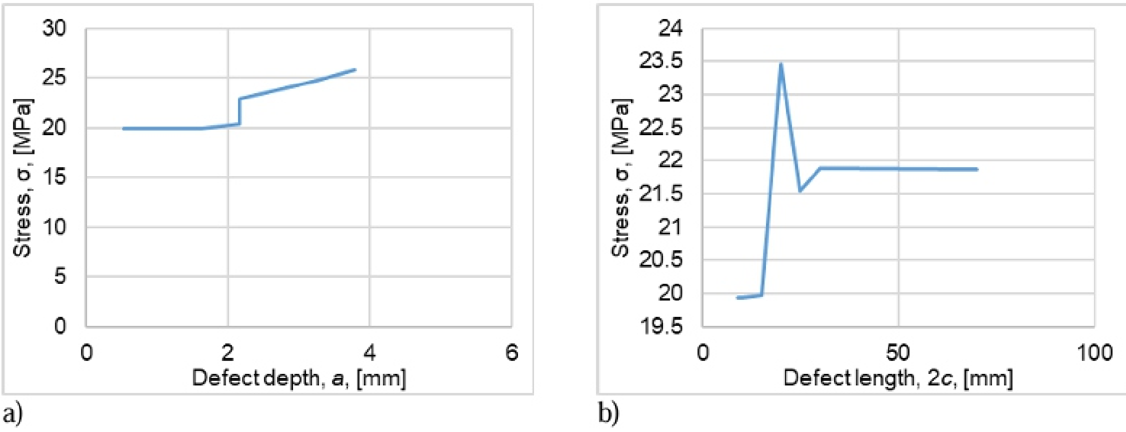

Figure 24. The influence of the geometric dimensions of the defect on the strength of the Pe100 polyethylene pipe evaluated under multiple stress conditions is shown in Figure 24.

4. Discussion

The determined value of the stress intensity factor, in the case of polyethylene pipe evaluated under multiple stress conditions, is given in Table 2, namely K_I = 0.7007 MPa·m$^{1/2}$. This value is lower than the critical value determined by (ALUCHI, 2013), namely K_{Ic} = 0.743 MPa·m$^{1/2}$. In this case, relation (1) is fulfilled.

The maximum value of the internal pressure recorded during the internal pressure stress of the PE100 pipe was $P_{i,max}$ = 33 bar. This was the value at which the pipe depressurization began – corresponding to the bursting time of 149 s – test fluid leaks occurred or the process of water leakage from inside the pipe was initiated.

The pipe failure was ductile, also known as “parrot beak” (figure 18).

By numerical evaluation, for the scratch-type defect, positioned in the GH 23-26 space, with 9 mm long and 1.2 mm deep, the strength value of the pipe (maximum stress developed in the pipe wall) was obtained as 19.937 MPa.

By successively changing the values of the depth and length of the defect, in percentages from 10% to 70% of the geometric dimensions of the pipe, it was found that the resistance has a nonlinear variation (figures 22 and figures 23), which can be explained by the viscoelastic behavior of the material.

Experimental and numerical results show that surface defects, such as scratches and microcracks, can significantly reduce the mechanical strength of PE100 polyethylene pipes. Preliminary experimental and numerical findings indicate that surface imperfections, including scratches and microcracks, can substantially diminish the mechanical strength of PE100 polyethylene pipes. A scratch-type defect, with a depth of just 1.2 mm (22.22% of the wall thickness), was sufficient to induce pipe rupture under internal pressure. This underscores the necessity for robust pipeline protection methods during installation and the establishment of more stringent standards for assessing the quality of these before utilization.

5. Conclusions

The tests and results obtained in the evaluation of the polyethylene pipe under multiple stress conditions are shown in summary table 4.

Table 4. Centralizer of tests and results obtained in the evaluation of the polyethylene pipe under multiple stress conditions

Test name	Results obtained, symbol and unit of measurement	Description/values						
Analytical evaluation	Stress intensity factor, K_I, [$MPa \cdot m^{1/2}$]	0.7007						
Traffic overload simulation	Identification of the defect in the form of a scratch	9 mm long and 1.2 mm deep positioned in the GH 23-26 space						
Internal pressure test	Burst pressure, P_I, [bar]	33						
	Burst time, t, [s]	149						
Numerical evaluation	Defect depth, a, [mm]	1.2	0.54	1.8	1.62	2.16	2.7	3.24
	Strength, σ, [MPa]	19.937	19.937	19.937	19.935	20.419	22.901	24.767
	Defect length, $2c$, [mm]	9	10	15	20	25	30	70
	Strength, σ, [MPa]	19.937	19.934	19.978	23.453	21.548	21.888	21.872

The study demonstrated that numerical modelling plays a crucial role in assessing the performance of PE100 polyethylene pipelines. It was found that numerical models can reduce the time necessary for conducting physical experiments and optimize the utilization of resources. Furthermore, the numerical results indicated that the depth and extent of defects significantly influence the mechanical behavior of the pipe, a finding corroborated by experimental evaluations.

Numerical modelling facilitates the simulation of multiple stress scenarios on pipelines by leveraging data from physical tests to optimize the identification of critical defect points, thereby reducing the need for extensive, costly, and time-consuming experimental tests, while the use of ANSYS software enables a rapid assessment of defect impact on pipeline strength and allows for the practical evaluation of multiple scenarios.

The use of hybrid approaches, integrating experimental testing with numerical simulations, can contribute to the development of more precise standards for the design and maintenance of underground pipelines.

This study emphasized the necessity for robust pipeline protection measures during installation and stricter standardized quality assessments to prevent premature failure and future work should focus on advanced monitoring techniques and protective coatings to enhance pipeline longevity and reliability.

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Acknowledgements

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