

SMART TECHNOLOGIES AND FLEXIBLE ROAD MAINTENANCE SYSTEMS VIA NANOMATERIALS

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Rezumat. Această cercetare examinează integrarea sistemelor flexibile de fabricație cu tehnologii inteligente pentru a îmbunătăți produsele existente utilizând materiale bazate pe nanotehnologie. Studiul evidențiază rolul flexibilității în adaptarea proceselor tehnologice la condiții variabile de operare și urmărește optimizarea soluțiilor de întreținere a drumurilor prin integrarea nanomaterialelor în compoziția asfaltului. În același timp, sunt analizate tehnologii inteligente precum monitorizarea, automatizarea și analiza datelor. Cercetarea propune un model aplicabil pentru creșterea sustenabilității infrastructurii, bazat pe reconfigurarea sistemelor flexibile. Rezultatele evidențiază potențialul acestor tehnologii de a reduce costurile de întreținere, de a crește eficiența operațională și de a dezvolta soluții durabile în ingineria drumurilor.

Abstract. This research examines the integration of flexible manufacturing systems with smart technologies to improve existing products using nanotechnology-based materials. The study highlights the role of flexibility in adapting technological processes to variable operating conditions and seeks to optimize road maintenance solutions by integrating nano-materials into asphalt composition. At the same time, smart technologies such as monitoring, automation, and data analysis are being analyzed. The research proposes an applicable model for increasing infrastructure sustainability, based on the reconfiguration of flexible systems. The results highlight the potential of these technologies to reduce maintenance costs, increase operational efficiency, and develop sustainable solutions in road engineering

Keywords: Nanomaterials, Road infrastructure maintenance, Smart Technologies

1. Introduction

Road infrastructure maintenance is undergoing a stage of structural transformation driven by traffic intensification, climate variability, the accelerated degradation of bituminous pavements, and budgetary constraints. In this context, the traditional approach based on reactive interventions is becoming insufficient, making it necessary to move toward predictive maintenance models capable of anticipating degradation, optimizing the prioritization of works, and reducing intervention times [3], [5], [10].

Within this framework, stockpiled asphalt mixtures and cold-applied bituminous materials are gaining increased operational relevance due to their ability to enable rapid interventions independent of complex thermo-energetic infrastructures. The evolution of these materials, from solutions regarded as temporary to technical

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systems optimized through high-performance emulsions, polymers, and nano-additives, reflects their technological maturation and the expansion of their field of application [1], [2]. Nevertheless, limitations such as low initial strength, moisture sensitivity, and storage stability indicate the need to integrate them into a systemic decision-making framework rather than to use them in isolation [1].

At the same time, the development of road-monitoring technologies based on sensors, advanced imaging, data fusion, machine-learning algorithms, and digital twin concepts has enabled the emergence of smart road infrastructures. In these systems, the physical condition of the road is continuously translated into digital information that can support diagnosis, forecasting, and intervention decisions. Maintenance thus becomes a cyber-physical process in which field data are directly integrated into infrastructure modeling and management [4], [5], [8], [9].

On this basis, the paper proposes a conceptual model of a smart flexible system for road maintenance, in which intervention materials, information flows, and the decision-making process are integrated into a unitary architecture. In this vision, storable asphalt mixtures are treated as active operational resources whose use is contextually determined by the state of the infrastructure and by system priorities.

The study follows two complementary directions. From a theoretical perspective, it substantiates an integrated smart flexible system model structured around informational, decisional, and operational subsystems interconnected through a feedback loop. This framework allows a unitary interpretation of the relationship among material, information, and intervention, going beyond the fragmented approaches found in the specialized literature [4], [5], [10]. From an applied perspective, the paper capitalizes on data regarding CARGOSFALT-type bituminous products, used as examples of storable materials with extended functionality. These materials demonstrate their integration potential within a smart maintenance system in which their activation is determined by the contextual analysis of degradation and decisional prioritization [6], [7]. Thus, the paper's contribution lies not only in describing innovative materials, but also in integrating them into an operational architecture for adaptive and predictive maintenance.

2. Need for the Transition to Advanced Functional Materials

2.1. From Passive Material to Functional Material

The durability of asphalt is not determined exclusively by construction parameters such as layer thickness or degree of compaction, but also by the material's ability to withstand the initial micro-degradation mechanisms that precede visible deterioration (Fig. 1).

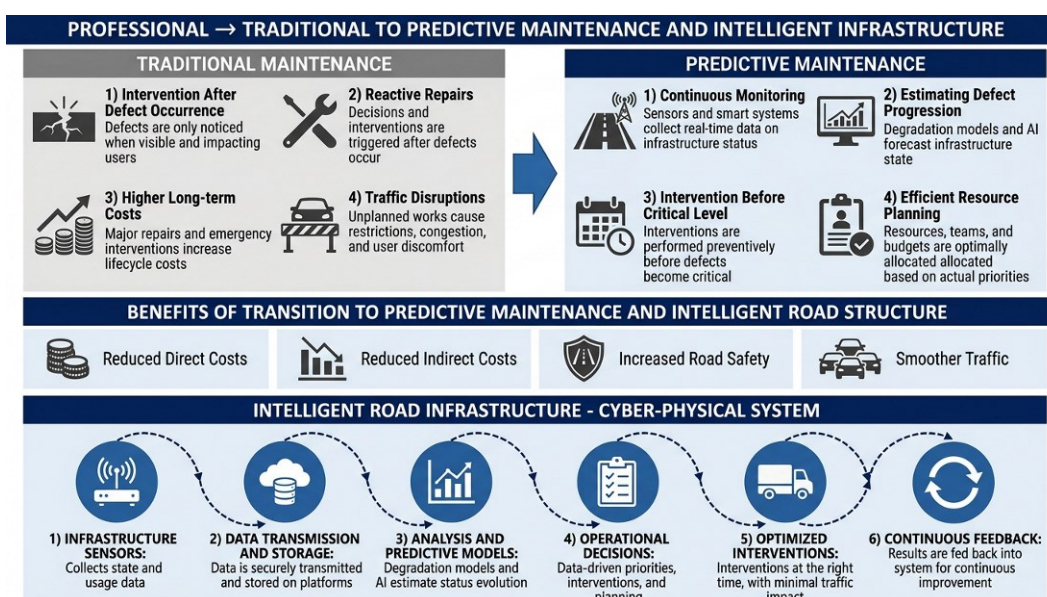


Fig. 1. Conceptual transition from asphalt as a passive covering material to functional asphalt as a material actuator of the maintenance system.

Modern asphalt therefore evolves from the role of a passive material to that of a functional material, designed to maintain its performance under variable conditions and to limit the initiation and propagation of cracks [1], [2].

This transition involves the adoption of chemical and structural modification solutions intended to improve fatigue resistance, reduce plastic deformation, and increase the service life of road infrastructure [1].

The notion of a smart road should not be reduced to spectacular infrastructures that are fully robotized or entirely sensorized. In operational terms, a road becomes smart when its condition can be perceived, interpreted, and used for timely decision-making. Consequently, infrastructure intelligence resides less in the isolated materiality of the road and more in the relationship among the physical asset, the data it produces, and the institutional capacity to intervene [3], [4], [5], [8].

In practical terms, this integration offers three major benefits: (i) reducing the delay between the emergence of degradation and intervention; (ii) using storable materials more efficiently, allocating them according to priority and context; and (iii) increasing the traceability of technical decisions, because each intervention can be justified by data and performance assessment.

2.2. Rationale for the Use of Nanotechnological Materials in Road Rehabilitation

Applying nano-technological materials in bitumen and asphalt mixtures makes it possible to modify rheological and mechanical properties at the micro-structural scale. Nano-additives contribute to improving adhesion between aggregates and binder, reducing thermal susceptibility, and increasing resistance to oxidative aging [1], [2].

Unlike conventional modifications based on polymers or recycled rubber, the nano-structural approach seeks not only to increase material rigidity, but also to control crack-initiation mechanisms. As a result, this technological solution creates the premises for increasing the durability of road structures and reducing the need for major interventions through less frequent and more predictable maintenance [1], [2].

2.3. Smart Technologies versus Flexible System. Emerging Directions

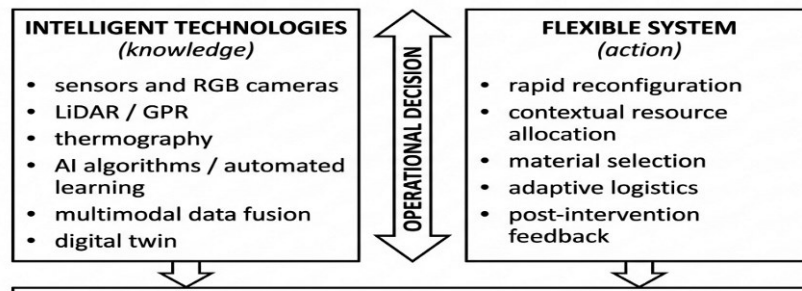


Fig. 2. Smart technologies versus flexible system - conceptual distinction.

Smart technologies and flexible systems are not synonymous concepts. Smart technology refers to the set of tools capable of observing, measuring, interpreting, and supporting decision-making: sensors, cameras, LiDAR (Light Detection and Ranging), GPR (Ground Penetrating Radar), thermography, artificial intelligence (AI) algorithms, data-fusion platforms, and digital twin (DT) systems [3], [4], [5], [8], [10] (Fig. 2). The flexible system represents the property of the operational architecture to reconfigure itself rapidly and efficiently according to changing operating conditions, priorities, defect type, and available material [5], [8]. Thus, intelligence provides knowledge, while flexibility ensures its conversion into optimal action.

The emerging direction in road-network management is predictive maintenance, in which intervention is no longer triggered exclusively by visible defects, but by the probability of imminent degradation. Predictive models estimate the deterioration trajectory, identify risk thresholds, and support the prioritization of works on engineering and economic grounds [3], [5], [10]. Smart infrastructure

presupposes the existence of a digital layer that reflects, almost in real time, the condition of the physical asset and allows intervention alternatives to be tested before field application [4], [5], [8].

Multimodal monitoring is essential: RGB cameras, thermal images, LiDAR, GPR, GPS, IMU (Inertial Measurement Unit), traffic and weather sensors, as well as data derived from inspection reports [4]. Each source captures a different dimension of degradation: surface geometry, visual defects, thermal anomalies, substructural problems, exact positioning, and temporal evolution. Malihi et al. [4] show that multimodal fusion produces a more complete picture of road assets, allowing the structuring of a robust basis for predictive maintenance. Likewise, the automatic detection of cracks and potholes through deep learning has become significantly more accurate with the adoption of neural networks [3].

Transforming raw data into operational decisions requires the use of the digital twin concept. A road DT is a dynamic digital representation of the physical asset, updated with field data and capable of supporting condition assessment, scenario simulation, and intervention planning [5], [8], [10]. Consilvio et al. [5] propose a digital-twin-based decision support system (DSS) for road maintenance in which information derived from inspection, analysis, and modeling is converted into operational recommendations. This logic is extended into a cyber-physical vision by Xu et al. [8], in which the DT coordinates monitoring, decision-making, and the execution of repairs, including through robotized and autonomous modules. In turn, Hui et al. [10] synthesize current research directions regarding the application of digital twin technologies in the construction and maintenance of road equipment, highlighting the need to integrate knowledge of materials with intervention logistics.

Therefore, flexible maintenance is defined as the adaptation of the type, timing, intensity, and logistics of the intervention on the basis of an updated digital image of the infrastructure - a flexibility that is both technological and decisional.

3. Conceptual Model of a Smart Flexible System for Road Maintenance

3.1. Premises and Conceptual Structure

The proposed model starts from the premise that efficient road maintenance must be organized as a functional relationship among three classes of elements: material, information, and action. The material is represented by the storable asphalt mixture or the bituminous intervention solution; the information is produced through continuous monitoring and analysis; the action is the technological and logistical intervention carried out in the field. Only the correlation of these three dimensions allows an authentic flexible system to be obtained (Fig. 3).

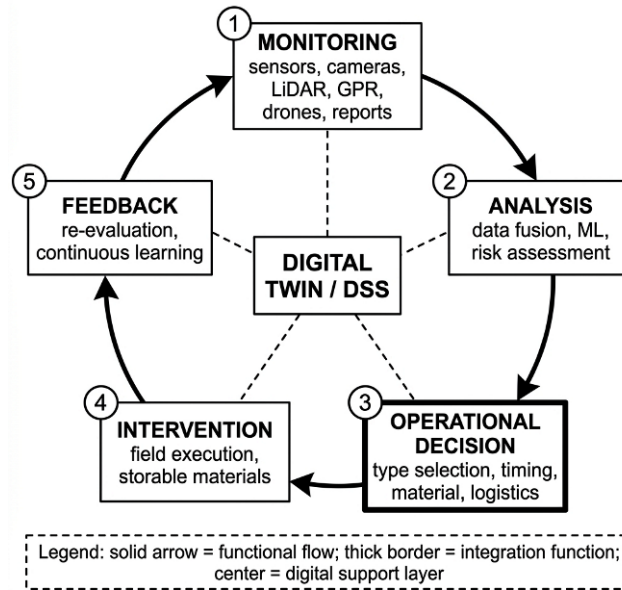


Fig. 3. Architecture of the smart flexible road maintenance system, structured as a closed loop: monitoring -> analysis -> operational decision -> intervention -> feedback. The digital twin layer and decision-support tools form the integrative core.

3.2. General Architecture: Monitoring -> Analysis -> Decision -> Intervention -> Feedback

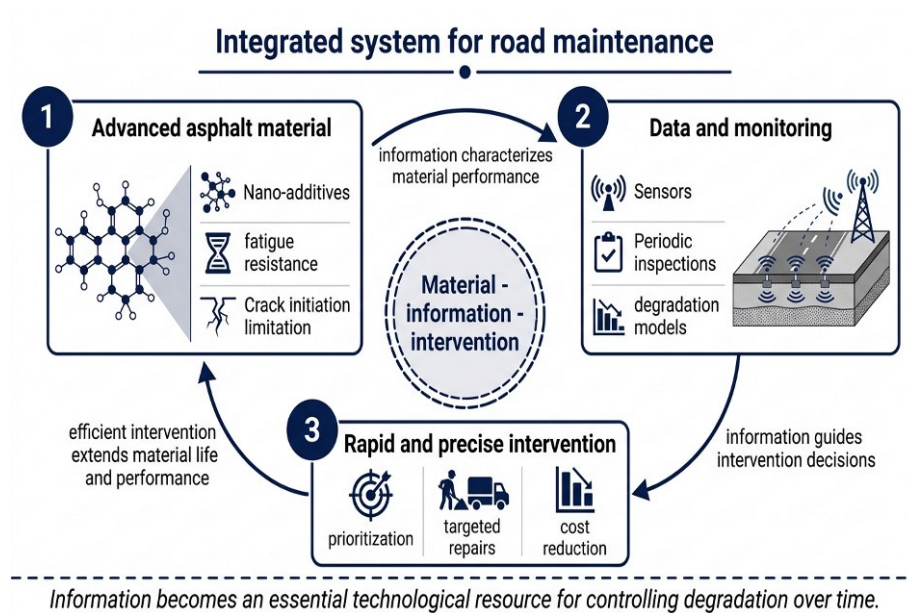


Fig. 4. Integrated system for road maintenance.

From this perspective, flexibility does not mean the existence of several types of equipment or materials, but the system's ability to rapidly reconfigure its response to road condition. The system must be able to move from monitoring to diagnosis, from diagnosis to decision, and from decision to intervention without major losses of time, with adequately dimensioned resources and with systematic feedback regarding the results obtained.

The proposed conceptual architecture is made up of three interdependent subsystems articulated through a feedback loop (Fig. 4):

- The informational subsystem collects data from road sensors, cameras, drones, LiDAR, GPR, inspection reports, and the history of works, its role being to transform physical degradation into exploitable information. It constitutes the system's knowledge base and the main source of inputs for the analytical level [3], [4]. The decisional subsystem integrates data fusion, predictive analysis, expert rules, and risk assessment. It establishes the nature of the degradation, its severity, the intervention priority, and the recommended type of material or procedure. In advanced forms, it is supported by the digital twin and by DSS (Decision Support System) tools [4], [5], [8], [10].

- The operational subsystem includes logistics, equipment, teams, application procedures, and storable materials. It ensures the actual implementation of the intervention, with the possibility of reconfiguration according to real field conditions. In this subsystem, the storable asphalt mixture is treated as a resource with high operational availability.

- The feedback loop closes the system: after the intervention, the surface condition is reassessed and the resulting data are reintegrated into the knowledge base. Maintenance thus becomes a process of continuous organizational and technological learning.

3.3. Operational Decision as an Integration Function

At the center of the proposed architecture lies a distinct conceptual function, referred to here as operational decision in maintenance. This represents the mechanism through which technical information produced by monitoring and analysis is converted into a concrete intervention, selected in relation to the available material, the severity of degradation, environmental conditions, traffic level, and the road administrator's objectives. Operational decision ensures the coherence of the system because it connects the cognitive level of smart infrastructure with the executive level of maintenance [4], [5], [8].

To function adequately, the operational decision must correlate at least four classes of variables: type of degradation, severity of the defect, environmental conditions, and traffic level. This correlation can be achieved through expert rules, machine-learning models, or simulations within a digital twin [5], [8], [10].

3.4. Typology of Intervention: Multiple Logics within a Unitary Decision System

The proposed model supports mixed maintenance, in which three action logics coexist: preventive, predictive, and corrective (Fig. 5). The novelty lies not in the simple coexistence of these three registers, but in their articulation through a single decision system that contextually selects the appropriate logic on the basis of the available data.

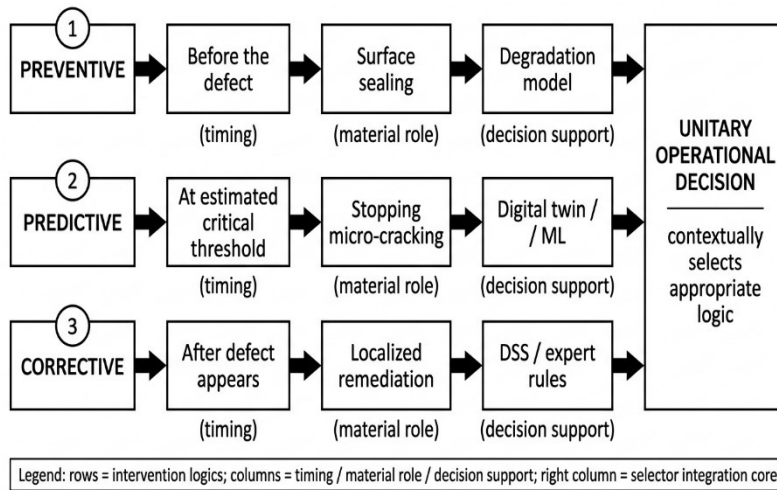


Fig. 5. Typology of interventions - preventive, predictive, and corrective - subsumed to a unified operational decision function that contextually selects the appropriate logic according to the available data.

In practice, the same storable material may be used differently depending on the system diagnosis: as a preventive sealing treatment, as a solution for stopping incipient degradation, or as a material for localized remediation. Therefore, its value is amplified by the intelligence of the architecture into which it is integrated.

4. Case Study: Integration of CARGOSFALT Nano-technological Materials

4.1. Functional Requirements of Smart Products

To be compatible with a smart flexible system, the material/product must simultaneously meet technological requirements (adequate adhesion, behavior in moisture, stability, integration into the existing layer) and operational requirements (rapid availability, easy handling, applicability under variable temperature and traffic conditions, compatibility with manual or mechanized interventions) [1], [2], [6], [7]. Storable mixtures and cold-applied solutions respond to this dual requirement by reducing dependence on the thermal chain and

allowing the intervention to be rapidly reconfigured according to location, the amplitude of degradation, and traffic constraints. In a smart system, these materials do not replace all classical solutions, but they become essential components for rapid and adaptive interventions.

4.2. General Characterization of CARGOSFALT Products

C. Gheorghe et al. describe, in publications appearing in the Annals of the Academy of Romanian Scientists [7] and in the PRODUCTICA Conference Proceedings [6], the development and use of innovative bitumen-based CARGOSFALT products for extending the service life of road infrastructure. The products are based on bitumen modified with polymer compounds and functional nano-additives and are intended to protect asphalt or cement-concrete surfaces against oxidation, water penetration, and the progression of microcracking [6], [7].

The CARGOSFALT system integrates three complementary intervention directions: preventive protection of asphalt surfaces, consolidation of structural interfaces, and regeneration of existing materials through cold recycling. In this approach, materials are treated as functional elements integrated into an adaptive maintenance process aimed at extending the service life of infrastructure and reducing the frequency of major interventions. Through their functional characteristics and compatibility with rapid and adaptive interventions, CARGOSFALT products support the transition from conventional road maintenance to a flexible and smart maintenance model in which the selection and use of materials are correlated with the type of degradation, operating conditions, and the operational objectives of the system.

Table 1. Functional properties of CARGOSFALT products and their systemic relevance.

<i>Functional property</i>	<i>Mechanism of action</i>	<i>Operational benefit</i>	<i>Product</i>
thermal barrier	reflective pigments + polymers	surface temperature reduction by 8-10 °C	UV (therm)
regeneration	molecular penetration	restoration of binder elasticity	UV (therm)
instant adhesion	100% active, without water	traffic reopened in 30 min	EBRC
deep penetration	controlled viscosity	anchorage in microcracks	EBRC
total recycling	reactivation of existing binder	zero waste, reduced cost	Concentrate (C)
impermeability	continuous film	protection against water/ice	all products

Within the proposed smart flexible system, three nano-technological bituminous products developed under the CARGOSFALT brand are analyzed separately as an illustration of material integration into the logic of smart maintenance (Table 1).

Their characterization is based on published technical data and on the author's direct experience in her capacity as CARGOSFALT product development.

4.3. Systemic Integration of CARGOSFALT Products into the Smart Maintenance Architecture

Within the proposed smart flexible system, the three products are used in a differentiated manner, depending on infrastructure diagnosis and the associated decisional logic (Fig. 6). In this framework, the material becomes a decisional actuator - the physical component through which the system responds to degradation.

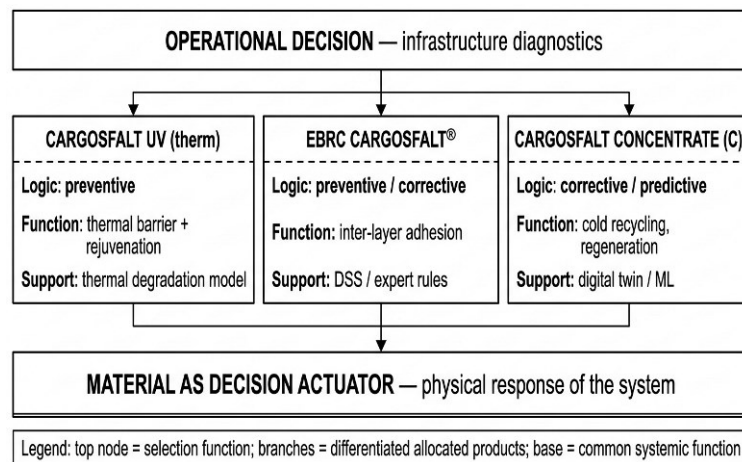


Fig. 6. Differentiated allocation of the three nanotechnological CARGOSFALT products (UV/therm, EBRC, and Concentrate C) within the architecture of the smart flexible system, according to the type of intervention logic and the associated decision support.

4.4. Systemic Significance: Material as a Decisional Actuator

From a conceptual point of view, storable CARGOSFALT-type bituminous products can be interpreted as material actuators of the system: the material is not merely stored and applied, but is decisionally activated according to the state of the infrastructure, becoming the physical component through which the system exerts its response to degradation [4], [5], [8].

Published in situ results regarding the behavior of CARGOSFALT products indicate improvements in the roughness of the treated surface, increased protection against water infiltration, and the potential to extend the service life of the road structure [6], [7]. Although these results do not exhaust the analysis of long-term performance, they support the integration of the material into an operational architecture oriented toward preventive maintenance and rapid corrective interventions.

In a smart flexible system, the selection of such a material must result from correlating at least four classes of variables: the type of degradation, its severity, environmental conditions, and traffic level. This correlation can be achieved through expert rules, machine-learning models, or simulations within a digital twin - and this is precisely the essential difference between the conventional use of a maintenance product and its integration into a smart system [5], [8], [10].

4.5. Implementation Scenarios

Comport The adaptive behavior of CARGOSFALT nanotechnological materials allows their integration into diverse operating scenarios:

- Urban roads with heavy traffic. The material's capacity to redistribute internal stresses and reduce the effects of structural fatigue makes it suitable for networks subject to frequent stops, abrupt acceleration, and high dynamic loads. Integration into a smart monitoring system allows the early identification of critical areas and the execution of localized, minimally invasive interventions [3], [6].
- Motorways and strategic infrastructures. The material's durability under the repetitive loads of heavy vehicles, combined with its compatibility with smart monitoring systems and autonomous execution, makes it possible to significantly reduce interruptions caused by maintenance works [7], [8], [10].
- Areas with extreme climatic variations. The nano-modified structure provides superior thermal stability and a high capacity to adapt to climatic stress, reducing the occurrence of thermal cracking and surface degradation in mountainous regions or areas with severe continental climates [1], [2], [9].

5. Conclusions and Original Contributions

The present paper aimed to substantiate, both theoretically and in applied terms, the way in which smart technologies and flexible systems can be articulated into a unitary road-maintenance architecture through nanotechnological materials. In direct relation to the paper's title, the research conclusions are structured on three complementary levels - technological, systemic, and material - each reflecting one of the essential components of the proposed concept.

At the level of smart technologies, it has been demonstrated that current tools for perceiving and analyzing road condition - sensors, RGB cameras, LiDAR, GPR, thermography, multimodal data fusion, machine-learning algorithms, and digital twin systems - have reached a degree of maturity that enables the transition from traditional periodic inspection to continuous, predictive, and contextual monitoring of road infrastructure. These technologies produce structured

knowledge about the physical asset, transforming degradation into information that is operationally useful from a decisional standpoint. Nevertheless, their value remains only potential as long as the generated information is not converted into optimal action through an explicit mechanism for selecting the intervention.

At the level of flexible systems, the paper substantiates an original conceptual model built on the functional relationship among material, information, and action, in which operational decision occupies the position of integration function. Flexibility, understood in this way, is not a logistical property of the equipment fleet, but a systemic characteristic expressed through the operational architecture's ability to reconfigure itself rapidly according to defect type, its severity, environmental conditions, and traffic level. Consequently, the proposed system is not only smart - because it uses advanced perception and analysis technologies - nor only flexible - because it can be reconfigured operationally - but both simultaneously, because the correlation of these two properties represents the ultimate criterion for evaluating its performance.

At the level of nano-technological materials, it has been highlighted that the application of nano-additives and polymer modifiers in the formulation of bitumen and asphalt mixtures does not represent merely an incremental improvement of physicochemical properties, but a functional reinterpretation of the material itself. Nano-modified storable materials become material actuators of the system, through which the technical response is effectively implemented in the field. The CARGOSFALT case study - analyzed through the three complementary products (UV/therm, EBRC, and Concentrate C) - confirmed the paper's central hypothesis: a coherent portfolio of nano-technological bituminous materials, applicable cold, can be differentially integrated into the preventive, predictive, and corrective logics of a smart flexible maintenance system.

Thus, in relation to the title of the paper, smart technologies, flexible systems, and nano-technological materials should not be treated as parallel development directions, but as the three convergent components of a unitary road-maintenance architecture. Smart technologies provide knowledge, flexible systems ensure its conversion into contextual action, and nanotechnological materials represent the physical response through which the system performs its maintenance function. Only their coherent integration, mediated by the operational decision function, transforms road maintenance from a succession of technical reactions into an adaptive, predictive, and traceable process.

In the broader perspective, the future of road maintenance is taking shape at the intersection of these three components: technologies capable of perceiving and interpreting degradation, systems capable of deciding rapidly and differentially, and nano-modified materials capable of providing a technically adapted response.

This paper offers both an original conceptual framework - articulated around operational decision as an integration function - and a concrete applied example through the CARGOSFALT case study, which is open to further development through experimental validation on pilot sectors, the development of dedicated DSS tools, and integration into national and European smart road-maintenance programs

List of Abbreviations and Acronyms

<i>Abbreviation</i>	<i>Definition in English</i>	<i>Definition translated from Romanian</i>
AI	Artificial Intelligence	artificial intelligence
CMA	Cold Mix Asphalt	cold asphalt mixture
DSS	Decision Support System	decision support system
DT	Digital Twin	digital twin (dynamic digital representation of the physical asset)
EBRC	(trade name)	EBRC CARGOSFALT active bituminous binder, without water in the composition
GPR	Ground Penetrating Radar	ground-penetrating radar
GPS	Global Positioning System	global positioning system
HMA	Hot Mix Asphalt	hot asphalt mixture
IMU	Inertial Measurement Unit	inertial measurement unit
IRI	International Roughness Index	international roughness index
LiDAR	Light Detection and Ranging	detection and measurement by laser light
ML	Machine Learning	machine learning
RAP	Reclaimed Asphalt Pavement	recovered (recycled) asphalt material
RGB	Red-Green-Blue	color model; visible-spectrum color image camera
SR EN	Romanian Standard - European Standard	Romanian standard harmonized at European level
TSR	Tensile Strength Ratio	tensile strength ratio (indicator of moisture resistance)
UAV	Unmanned Aerial Vehicle	unmanned aerial vehicle (drone)
UV	Ultraviolet	ultraviolet radiation

Material actuator = a storable bituminous material, cold applicable, that receives commands from the decisional subsystem of a smart flexible road-maintenance system and physically executes them on the infrastructure, having the capacity to be used in different roles (preventive, predictive, corrective) depending on diagnosis, while its effects are measured and reintroduced into the system's feedback loop for continuous learning.

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