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Methodological Framework for Sustainable Transport Corridor Modeling Using Petri Nets

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Abstract: Current models for evaluating sustainable transport corridors often lack a comprehensive framework capturing the multifaceted performance measures vital for holistic assessment especially at the early stages of operation, when detailed information on the performance indicators of these transport corridors is not available. This gap motivates a Petri net-based modeling approach that integrates key sustainability indicators into a flexible simulation tool. This paper details a versatile methodology harnessing Petri nets, specifically Evaluation Petri nets (E-Nets), to assess corridor sustainability across environmental, social, and economic dimensions. The proposed framework equips planners and policymakers to explore diverse green corridor configurations under varying conditions. Case studies showcase the model's capabilities in analyzing real-world corridors, identifying performance bottlenecks, and comparing alternative solutions. The model provides a practical decision-support tool to strengthen strategies for efficient, socially responsible, and environmentally sound transport infrastructure. This research advances the theoretical foundations and demonstrates the practical value of Petri nets as an enabling methodology for modeling the intricate dynamics of sustainable transport corridors. This paper demonstrates how E-Nets provide a visual and quantitative representation of transport operations, enabling stakeholders to identify inefficiencies and potential improvements. This paper discusses the theoretical underpinnings of the E-Net modeling of transport corridors, the advantages and limitations of its application, and suggests avenues for future research to enhance the model's predictive power and real-world application. The paper concludes that the E-Net approach is a scalable, adaptable tool that can significantly con-tribute to the sustainable development of international transport corridors, providing a framework for continuous improvement in alignment with global sustainability objectives.

Keywords: sustainable transport corridors; Petri nets; key sustainability indicators; green infrastructure; environmental impact; models of transport corridors

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1. Introduction

The international transport corridors serve as the backbone of global trade and commerce, facilitating the movement of goods and passengers across various regions and countries. Traditionally, these corridors have been optimized for efficiency and capacity, emphasizing the speed and volume of transit.

However, with such expansion, the environmental implications become more pronounced, often leading to detrimental impacts on our planet. The realization of these environmental concerns, combined with the urgency to address climate change, has given birth to the concept of green transport corridors [1].

The concept of green transport corridors has emerged as a pivotal paradigm in the realm of international trade and sustainable development. These corridors are not merely redesigned pathways for the transit of goods; they represent a fundamental shift in the approach to the efficiency, environmental impact, and resilience of global supply chains.

As the world gravitates towards more sustainable practices, the transportation sector, being one of the significant contributors to greenhouse gas emissions, is undergoing a green transformation. This transformation encompasses a broad spectrum of interventions, ranging from the incorporation of renewable energy sources and energy-efficient technologies to the adoption of eco-friendly logistics and operational practices.

However, the nascent nature of green transport corridors brings forth a set of unique challenges. One of the primary hurdles is the evaluation of the effectiveness of such corridors in achieving their intended environmental and economic objectives. Traditional metrics and models employed for assessing transport corridors may not fully capture the nuances of their green counterparts. Therefore, there is a pressing need for novel approaches to model and analyze green transport corridors to facilitate their planning, implementation, and continuous improvement.

This study aims to address this gap by proposing an innovative approach to modeling green transport corridors with Petri nets as a modeling tool. This study seeks to create a robust framework for evaluating the multifaceted aspects of green transport corridors, including their environmental impact, economic efficiency, and operational resilience.

In this article, we also delineate the strategical, tactical, and operational levels of sustainable transport corridors. At the strategic level, the focus is on setting long-term goals and policies to foster sustainability in transport. The tactical level involves mid-term planning and resource allocation to align with these strategic objectives. Finally, the operational level concerns the day-to-day management and implementation of strategies and plans, ensuring the effective functioning of green transport corridors.

The structure of the paper is organized as follows.

Section 2 will develop an extensive literature review, examining the current state of research in sustainable transport corridors. This section will explore different previously employed approaches and methodologies, setting the context for our proposed model and highlighting the necessity for an innovative approach.

In Section 3, we will present the materials and methods used in our study. This section is dedicated to a detailed exposition of the Petri net methodology, elaborating on how it can be effectively applied to model the dynamics of sustainable transport corridors. We will discuss the specifics of constructing and implementing the model, providing a clear understanding of its functionality and potential applications.

Section 4 will then focus on the results of our modeling efforts. Here, we will showcase the practical applications of our Petri net model through various case studies, demonstrating its efficacy in analyzing and optimizing sustainable transport corridors. The section will also discuss how our findings contribute to the existing body of knowledge and the implications they hold for future corridor development.

Following the presentation of results, Section 5 will engage in an in-depth discussion. We will analyze the implications of our findings, both from practical and theoretical perspectives, and contemplate future research directions that stem from our study. This section aims to contextualize our research within the broader framework of sustainable transport and logistics.

Finally, Section 6 will conclude the paper. This section will summarize our key findings, reiterate the significance of our contributions to the field, and reflect on the broader implications of our research for policymakers, industry stakeholders, and the academic community.

2. Related Works

The academic inquiry into sustainable transport corridors has burgeoned over recent years, spurred by escalating environmental concerns and the pressing need for efficient transport systems. This section provides a review of the pertinent literature, spanning various approaches to sustainability in transport corridor development and management.

2.1. Reviews of the Literature on Sustainable Transport Corridors

Paper [2] thoroughly investigates the hurdles in creating a decarbonized transport system, identifies sustainable practices to reduce greenhouse gases, and reviews cutting-edge research enhancing transport sustainability. Through a systematic literature review, it delves into the primary barriers to sustainable transportation across regulatory, technological, financial, organizational, and social aspects. The paper then explores new methods promoting sustainable transport and discusses key policy measures to encourage sustainable mobility. The insights offered are intended to aid managers and policymakers in comprehensively understanding and building sustainable transport systems.

Study [3] analyzes the relationship between sustainable transport infrastructure and economic returns through bibliometric and visualization analysis from 2000 to 2019. The results highlight key articles, journals, and authors contributing to sustainable transport infrastructure research and define sub-areas and themes within this field. The study observes the evolution of major topics over two decades and anticipates shifts in future research directions. Conclusively, it provides insights that could guide further research on sustainable transport systems.

Book [4] emphasizes the significance of corridor concepts in economic development, highlighting their role in establishing efficient and sustainable logistics systems. The discussion encompasses various types of corridors including development, economic, multimodal transport, transit, trade, logistics, core corridors, and ancillary networks. The focus of the book is particularly on the concept of multimodal transport corridors.

2.2. Early Frameworks and Conceptualizations

The genesis of sustainable transport corridor discussions can be traced back to works like [5,6], who laid the groundwork by integrating the principles of sustainable development into transport planning. These pioneering studies were instrumental in introducing sustainability considerations into the discourse on transport infrastructure.

Paper [7] provides a comprehensive quantitative review of the economic impacts of transport corridors focusing on roads, rails, and waterways. A meta-analysis reveals that such infrastructure projects generally boost economic welfare and equity but can negatively impact environmental quality and social inclusion. The study suggests that policymakers should implement complementary measures to mitigate potential downsides, highlighting the need for more research to understand the diverse effects across different areas and communities.

Article [8] reviews various studies on the development of transport networks, advocating for a unified methodology in designing multimodal transport networks (MTNs). It introduces a set-theoretic model that outlines strategies for altering the structure and capacity of MTN components. This model serves as the mathematical foundation for the proposed methodology of MTN design and its subsequent evolution.

Paper [9] introduces a forward-looking methodology to predict future port transit throughput volumes, combining scenario planning, econometrics, and heuristic calculations. Central to the method are gravity models for estimating potential international trade flows and a novel approach for assessing transport corridors' attractiveness. The study uses a global business network approach to develop various scenarios based on key domestic and international factors. It quantitatively evaluates the effects of these factors on port throughput across different goods categories, assigning trade flows to the most attractive corridors. This methodology offers valuable insights for port authorities globally in strategic planning amidst uncertainties in international trade and logistics.

Article [10] presents an analysis, modeling, and performance assessment of supply chains utilizing long-distance intercontinental intermodal rail/road and sea-shipping freight transport corridors. The study establishes a methodology to evaluate the operational, economic, environmental, and social performance of these corridors, considering their infrastructural and technical capabilities. Using "what-if" scenario analysis, the methodology is applied to assess the performance of inland and maritime freight transport corridors between China and Europe, as part of the “Silk Road Economic Belt” and “A New Maritime Silk Road” initiatives. The findings suggest that the intermodal inland rail/road option could be a competitive alternative to maritime routes under certain conditions, though significant investments in inland infrastructure are necessary to effectively connect China with Europe.

The environmental challenges posed by transit transportation in the Land–Sea Corridor are discussed in paper [11]. The article identifies challenges in establishing this framework, including limited ecological security capacity in transit countries, inadequate collective international environmental efforts, misuse of environmental protections causing trade barriers, and conflicting legal outcomes in environmental lawsuits.

2.3. Modeling and Assessment Techniques

With the emergence of sustainability as a critical objective, researchers began to focus on quantitative models. Notable contributions include the work of McKinnon [12], who introduced a framework for measuring the carbon footprint of logistics activities, and Piecyk and McKinnon [13], who provided methodologies for assessing the environmental impact of transport corridors. These studies underscored the need for reliable data and robust modeling techniques in the appraisal of transport corridors.

Study [14] investigates the long-term effects of the Kazakhstan infrastructure program on national firm behavior, using dynamic panel data regression and micro shipping data to track transport connectivity over a decade. The findings indicate significant reductions in transport costs, with market accessibility proving crucial for enhancing firm productivity.

The model using fuzzy logic for evaluating urban transport sustainability, addressing key dimensions like economic, social, environmental sustainability, and transportation system effectiveness, is introduced in article [15]. The model, validated against traditional methods, identifies transport sustainability indicators from the literature and calculates a transport sustainability index, pinpointing areas for improvement.

Survey [16] reviews the growing research of models and algorithms for optimizing shared mobility. It categorizes shared mobility into ride-sharing and combined parcel–people transportation, exploring various optimization approaches. The paper differentiates between prearranged and real-time solutions, offering an overview of practical applications and suggesting future research directions in this evolving field.

A modified version of Dijkstra’s algorithm for finding the shortest routes in a road-transport network, reformulating the transport problem into a classical matrix format, is presented in [17]. This adaptation enables the application of various methods for constructing optimal transport plans, particularly for freight transportation along international transport corridors. The study uses analysis and modeling to improve route-finding methods on such networks, with the modified algorithm allowing for a table of connections to be represented. A software complex, developed in Delphi, was created to test this approach, focusing on optimizing freight traffic within Ukrainian and Western European transport systems.

Article [18] explores the use of the autoregressive distributed lag (ARDL) model to analyze international transport corridors, with a particular focus on adapting to changes in the Arctic transport environment due to polar ice melting. The study constructs models for the Northern Sea Route, the Trans-Siberian Railway, the Southern Sea Route (Suez Canal corridor), and the Northwest Passage, examining various natural, organizational, technological, and economic factors influencing these corridors. Key variables, such as GDP, the number of ships, icebreaker counts, tariffs, ice coverage, and cargo volumes, are incorporated as exogenous factors impacting the volume of transit traffic, the model’s endogenous variable. The methodology includes flux balance analysis, autocorrelation, and multicollinearity analysis of these variables.

The key challenges and prospective projects in developing the logistics system of the New Silk Road are examined in paper [19]. It explores the structure and global transport and logistics services market and the existing and potential networks of transport and logistics centers within the international transport corridors. The paper presents a technological model for the operation of railway terminals and introduces principles for modeling interactions among international transport corridor stakeholders. These include formalized models for the functioning of carriers, logistics centers, and their combined operations.

2.4. Policy and Regulation

Policy-driven research has been pivotal in shaping sustainable transport corridors. Studies such as those by Santos et al. [20] have scrutinized the efficacy of policy instruments in promoting sustainable transport.

Paper [21] evaluates the Belt and Road Initiative's capacity to achieve sustained economic, social, and environmental gains through transport corridors. It draws lessons from historical corridor development and analyzes effective sustainable policy interventions. The conclusion emphasizes the critical role of strong governmental policies and international agreements in maximizing the benefits of such infrastructure projects.

The European Bank for Reconstruction and Development study [22], supported by the EU, aimed to enhance sustainable transport links between Central Asia and the EU, focusing on environmentally, socially, economically, and politically sustainable corridors. The study was part of the EU's Global Gateway Strategy and sought to establish a sustainable network, promoting regional economic integration and development in line with the EU's strategy for the region. It identified the most viable routes and actions for development, including the Central Trans-Caspian Network as a key sustainable option, which could provide significant economic benefits by improving connectivity among Central Asian states and with Europe.

The TRIMODE integrated model, a comprehensive tool for assessing major transport infrastructure projects and policies in Europe, is described in [23]. TRIMODE combines transport, economy, and energy system simulations within a single software platform. It features a detailed transport model for both passenger and freight movements across Europe, including a full four-stage process (generation, distribution, mode sequence choice, and assignment), an energy model with dynamic vehicle fleets across all transport modes, and a macroeconomic model representing European countries' complete economic systems. The model offers high spatial resolution, focusing on the European Union and neighboring countries, with multimodal networks and zoning systems based on the NUTS III level and below. It provides detailed transport demand disaggregation and incorporates comprehensive vehicle fleet models for various transportation modes and energy sources. The paper particularly highlights the passenger modeling aspect within the EU-wide scale model, using PTV Visum software (https://www.ptvgroup.com/en/, accessed on 15 December 2023) and Python (https://www.python.org/, accessed on 15 December 2023) scripts for tasks beyond standard software functionalities.

Study [24] evaluates the impact of logistics policies and infrastructure development on cross-border transport in Central Asia (CA), which is crucial for landlocked CA countries. Under the CA Regional Economic Cooperation (CAREC) Program, led by the Asian Development Bank, the study employs a network equilibrium assignment model for simulation analysis. It utilizes the Global Logistics Intermodal Network Simulation (GLINS) model, covering various freight transport networks across Eurasia, to simulate the effects of logistics policies on the TCTC, particularly focusing on ferry service and rail network improvements. The findings endorse Kazakhstan's strategy that prioritizes transit time reduction and transport tariffs, alongside fostering cooperation within the Trans-Caspian International Transport Route Association.

2.5. Sustainable Infrastructure and Green Corridors

The concept of "green corridors", representing transport pathways optimized for minimal environmental impact, has gained traction.

Paper [25] conducts a review of transportation infrastructure's role in sustainable development. It employs co-author, co-occurrence, and co-citation analyses, alongside an examination of key concepts, to reveal emerging research trends and challenges. Visual graphs highlight influential authors and collaborative relationships between institutions in developed and developing countries. The review identifies critical issues like cost overruns and local development impacts. It suggests future research directions, including integrated effect studies and transportation network structure analysis, offering a visually expressive overview to aid researchers and practitioners in understanding the multifaceted impacts of transportation infrastructure on sustainability.

The concept of "green infrastructure" is explored for its historical roots and its modern innovation within environmental planning. This term, while not new in the context of landscape and open space planning, gains novelty when paired with "infrastructure", traditionally linked with technical or social constructs. Paper [26] scrutinizes the term's definitions and considers international cases to understand its relationship with conventional infrastructure types. It underscores the critical integration of green and blue spaces, akin to traditional infrastructure, especially given the escalating climate and biodiversity emergencies, and calls for robust management to realize its full benefits.

Paper [27] addresses the pressing need for sustainable transportation in light of growing urbanization and air pollution challenges in major cities. It critically reviews factors essential for implementing green transportation, identifying barriers, and proposing a three-step ASI strategy (Avoid, Shift, Improve) to tackle these challenges. The study examines innovative technologies and management approaches to green public transport systems and presents successful case studies demonstrating the ASI strategy's effectiveness. The findings offer valuable guidance for urban planning focused on sustainable, green transportation solutions.

The methodology for monitoring freight corridor performance, designed for sustainability assessments and initiated by the EU-funded SuperGreen project, is introduced in paper [28]. The methodology entails the periodic monitoring of transport chains along the corridor using Key Performance Indicators (KPIs), involving the decomposition of the corridor into chains, selection of typical chains, assessment through KPIs, and aggregation to corridor-level indicators with appropriate weights. A key aspect is the selection of sample chains and weight calculation, which combines transport model usage for initial sample construction and weight calculation with stakeholder refinement. The methodology's effectiveness was tested on the GreCOR project using the Danish National Traffic Model, showing promising results for freight corridor performance assessment and suggesting possible improvements.

2.6. Socio-Economic Dimensions

Recognizing that sustainability transcends environmental concerns, recent scholarship has adopted a more holistic perspective. Litman [29] extended the dialogue to encompass the social and economic dimensions of sustainable transport corridors, advocating for equity and access as integral components of sustainability assessments.

Study [30] presents a global overview of green logistics practices at various management levels and the inherent challenges of their implementation in emerging markets. It begins by clarifying the terminology and describing its scope and characteristics, and it continues with an analysis of the impact of green logistics on the creation of economic and social value.

Empirical study [31] investigates the impact of international transport corridors on regional economic development. It establishes a statistical relationship between the development indicators of these corridors and the economic growth of the regions they traverse. Using multidimensional regression analysis, the study identifies key economic factors influencing corridor development and how various corridor indicators affect regional economies. The findings reveal a significant interdependence between regional socio-economic development and transport corridor infrastructure, highlighting the need for careful consideration in investment and transport policy planning to foster economic growth and bilateral development.

2.7. Multimodal Integration

The integration of multiple modes of transport within corridors is another salient theme in contemporary research. The works in [32] have emphasized the importance of intermodality in achieving sustainability goals, presenting multimodal solutions as key to reducing transport sector emissions.

The multi-criteria evaluation of rail/road intermodal freight corridors as competitive transport alternatives is discussed in [33]. It introduces a methodology comprising analytical models to estimate various performance indicators (physical/spatial, infrastructural, technical, operational, economic, social, and environmental) and a Multi-Criteria Decision Making (MCDM) method to rank and identify preferred options among competing freight transport corridors. Applied to two Trans-European intermodal rail/road freight corridors, the methodology proves useful not only for researchers but also for decision makers like freight shippers/receivers, transport and terminal operators, infrastructure providers, and policymakers. It assists in allocating limited investments effectively across local, regional, national, and international infrastructures.

2.8. Tools Used in the European Union for Modeling of International Transport Corridors

Modeling and simulation play a vital role in transport planning and infrastructure development across Europe [34]. A variety of quantitative modeling approaches are utilized for forecasting travel demand, assessing economic impacts, and evaluating transport projects for major European transport corridors.

Four-step models remain the most widely adopted approach for travel demand modeling [35,36]. There is a wide spectrum of reviews on traffic simulation tools in the literature (e.g., [37,38]). Some examples of the mostly used micro- and macrosimulation tools introduced in these reviews are CUBE Dynasim [39], Paramics [40], EMME [41], SimTraffic [42], AIMSUN [43], VISSIM [44], and MatSIM [45]. These models provide granular analysis of user flows on transport networks, enabling infrastructure planning and investment decisions. More advanced dynamic traffic assignment versions account for congestion and transit schedules when assigning routes.

For wider economic assessments, computable general equilibrium (CGE) models like GTAP [46] and GEM-E3 [47] are often used. They capture economy-wide supply chains, trade links, market interactions, and the impact of transport on competitiveness across sectors. However, they lack the sectoral detail offered by partial equilibrium models focused specifically on transport.

There are a lot of actual modeling applications used in the European Union for simulating international transport corridors; here are some of the key tools and software applications:

- TRANS-TOOLS (Transport Network Analysis Tools) [48] is a comprehensive transport model developed for the analysis of European transport policies. It covers all modes of transport and is widely used for policy assessment and transport network analysis in the EU.
- The NEAC (Network of European–African Corridors) Model [49] is specifically designed for simulating and analyzing the transport corridors that connect Europe and Africa, focusing on trade and transport efficiency.
- ETISplus (European Transport Policy Information System) [50] provides an integrated database and modeling framework for transport policy analysis in Europe. It includes tools for forecasting and evaluating transport demand, modal splits, and infrastructure impacts.
- REVENUE (REVENue Use from Transport Pricing in Europe) [51] is a specialized tool used for assessing the revenue implications and economic effects of transport pricing policies across European corridors.
- ASTRA (Assessment of Transport Strategies) [52] is a model used for long-term policy assessment in European transport corridors. It integrates economic, social, and environmental aspects and is suitable for analyzing the impacts of various transport strategies.

- TRUST (Transport Research for Environmental Sustainable Transport) [53]: This model is used to assess the environmental sustainability of transport corridors, focusing on aspects like emissions, energy use, and ecological impact.

The methodology proposed in the paper, which is based on Petri nets, is intentionally designed to be universal and not constrained by pre-existing models, such as those adopted within the European Union. This universality allows for the application of our methodology to emerging transport corridors where detailed characteristics, including Technical Specifications for Interoperability (TSI) that are mandated in EU countries, may not yet be fully defined. The versatility of Petri nets enables the modeling of these nascent corridors in a way that traditional EU-centric models may not accommodate due to their reliance on established parameters and specifications.

Our Petri nets modeling approach is particularly suitable for the conceptual phase of new transport corridors, where information is often incomplete or speculative. Unlike standard models which require detailed inputs consistent with EU Corridors methodology and TSI, Petri nets can begin with a high-level representation and incrementally incorporate details as they become available. This iterative and flexible modeling process is essential for the initial planning and design stages of new corridor development.

In the pursuit of environmentally sustainable solutions for transport logistics, the concept of green transport corridors has emerged as a critical focal point. These corridors aim to enhance the efficiency and sustainability of transport operations by leveraging multimodal systems and innovative logistics solutions. However, the scholarly literature reveals a distinct gap in the development of robust, holistic models for the evaluation of such corridors' effectiveness with respect to sustainability criteria.

While there is a considerable body of literature that delves into individual aspects of green transport corridors, such as emission reduction techniques, energy efficiency, and policy frameworks, there is a noticeable absence of comprehensive models capable of capturing the complex, multifaceted nature of sustainability. Existing studies often address singular aspects of green corridors, such as the environmental impact, without integrating the economic and social dimensions that are equally pivotal to comprehensive sustainability assessments.

This paper addresses the existing gap by introducing a model based on Petri nets—a mathematical modeling tool used to describe and analyze the flow of resources in discrete event systems.

The use of Petri nets for modeling international transport corridors with a sustainability focus offers a comprehensive, intuitive, and adaptable framework that provides a clear advantage over traditional transport models. The approach is particularly well-suited to address the multifaceted challenges of modern transport systems, ensuring that sustainability considerations are central to the analysis and decision-making processes:

- Petri nets allow for a granular level of modeling that captures both the static and dynamic aspects of transport corridors. Unlike traditional models that may focus on steady-state analysis, Petri nets can model the system in a state of flux, which is critical for capturing the real-life operations of transport corridors that are inherently dynamic.
- The proposed Petri net model integrates sustainability indicators directly into the structure of the model. This is a significant departure from other models that might consider sustainability as an afterthought or a secondary layer of analysis. By embedding indicators like carbon emissions, energy consumption, and socio-economic impacts into the core of the model, the Petri net approach ensures that sustainability is a primary focus rather than a peripheral concern.
- Petri nets provide a visual representation of complex systems, which is not always the case with algebraic or computational models. This visual framework is not only intuitive, allowing stakeholders to understand and engage with the model more effectively, but it also helps in identifying inefficiencies and potential improvements in the transport corridor.

- International transport corridors are inherently multimodal, involving roads, rail, ports, and more. Petri nets excel at modeling such multimodal systems, capturing the interactions and interdependencies between different modes of transportation. This contrasts with other models that might be tailored to specific transportation modes and less capable of handling the complexities of multimodal systems.
- The Petri net methodology is highly scalable and flexible. It can be adapted to corridors of different sizes and complexities with relative ease. Other models may require significant adjustments or may not scale well, leading to a loss of accuracy or increased complexity in the model.
- Petri nets can incorporate both stochastic (random) and deterministic elements. This dual capability allows the model to reflect the unpredictable nature of real-world transport corridors more accurately, where delays and other random events can have significant impacts.
- The methodology can simulate the impact of different operational strategies and policies, enabling policymakers to evaluate the potential effects of their decisions before implementation. This proactive approach can lead to more informed and effective policies for sustainable transport.
- Petri nets can be designed to factor in various compliance measures and interoperability standards, which are essential for international transport corridors spanning multiple countries with different regulations. This built-in compliance ensures that the model remains relevant and applicable across different legal and operational environments.

Petri nets are particularly well-suited for this purpose due to their graphical nature and ability to model concurrent processes. By extending Petri nets with sustainability indicators, it becomes possible to simulate and evaluate the performance of green transport corridors under different operational scenarios and policy conditions. This approach allows for dynamic assessment, where the impact of changes in the network can be immediately observed and analyzed.

3. Materials and Methods

3.1. Concept of Green Transport Corridors

Green transport corridors can be defined as multimodal transport networks designed with a focus on sustainability. They aim to minimize the environmental impact of transport activities by incorporating advanced technologies, renewable energy, and eco-friendly practices. These corridors are not just physical pathways but are also embedded with intelligent systems for efficient and sustainable logistics and operations.

The multifaceted nature of sustainability within the context of international transport corridors necessitates a nuanced and comprehensive understanding of the various aspects that contribute to their long-term viability and responsibility. As these corridors become increasingly crucial in facilitating global trade, there is a growing recognition of the need to balance economic efficiency with environmental stewardship and social well-being. This balance is essential not only to preserve our planet but also to ensure equitable benefits for all stakeholders involved.

The review of the existing literature on green transport corridors underscores a research gap in comprehensive and quantitative modeling approaches for sustainability analysis. While the literature covers conceptual principles and qualitative discussions, there is a lack of mathematical models that integrate the multidimensional aspects of sustainability within a single framework.

This provides the motivation for the novel E-Net model developed in this paper, which aims to address this gap through a quantitative, visually executable modeling platform. The model encapsulates the breadth of sustainability factors discussed in the literature within a cohesive Petri net-based structure suited for dynamic simulation and analysis.

Therefore, the literature review serves to highlight the need for the original E-Net contribution presented here. This model provides an advancement in leveraging the capabilities of Petri nets to quantitatively evaluate and optimize the sustainability of transport corridors in a holistic manner.

Modeling serves distinct purposes at different management levels. At a strategic level, it facilitates the understanding of the long-term impacts of sustainable corridors. Tactically, it aids in resource optimization and route planning. Operationally, modeling is crucial for the efficient day-to-day management of corridor activities and monitoring adherence to sustainability standards.

Our modeling approach is designed to encapsulate both the physical and operational aspects of transport corridors. It not only considers the tangible infrastructure components but also integrates the operational strategies and processes that are crucial for achieving sustainability.

To better conceptualize and operationalize sustainability in international transport corridors, a structured taxonomy can be proposed (Figure 1). Such a taxonomy serves as a blueprint for identifying, categorizing, and prioritizing the different elements that constitute sustainable practices within these corridors. It offers a guide for policymakers, researchers, and practitioners to systematically approach the complexity of creating transport pathways that are economically viable, environmentally sound, and socially responsible.

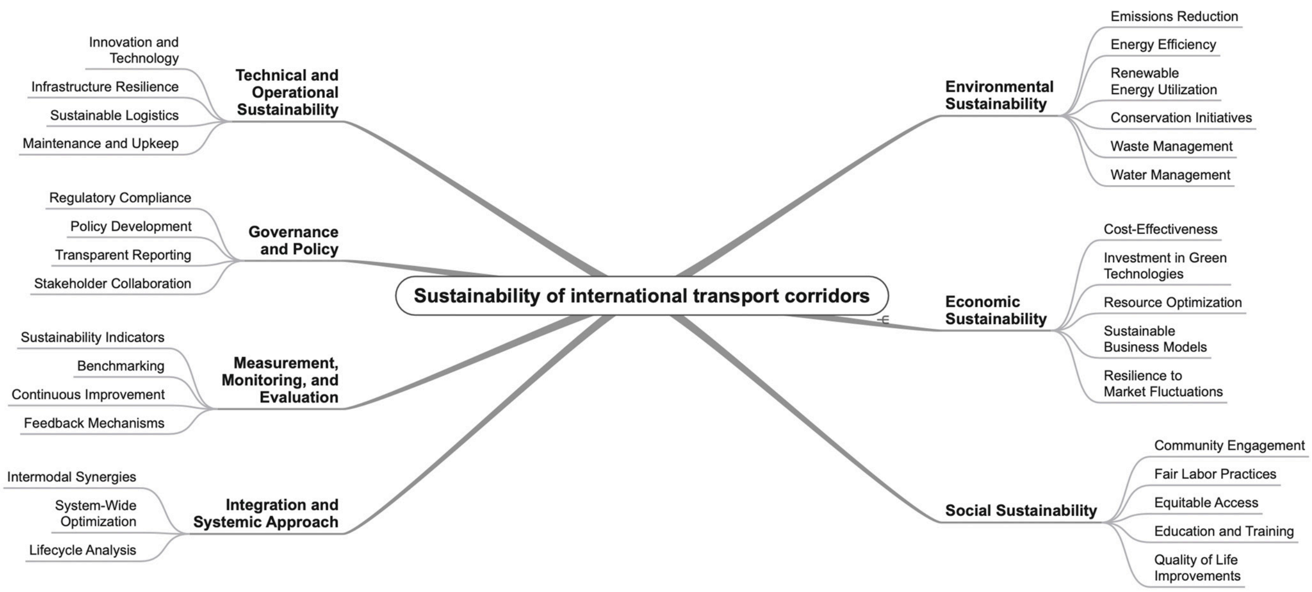

Figure 1. Taxonomy of sustainability of transport corridors.

The proposed taxonomy delineates sustainability into seven overarching domains: Environmental Sustainability; Economic Sustainability; Social Sustainability; Technical and Operational Sustainability; Governance and Policy; Measurement, Monitoring, and Evaluation; and Integration and Systemic Approach. Each of these domains encompasses a range of criteria that measure the corridors' sustainability. A brief description of the taxonomy main components is presented in Table 1.

Environmental Sustainability focuses on the natural world and the corridors' impact on ecosystems, encompassing efforts from reducing emissions to water management. Economic Sustainability tackles the financial aspects, ensuring that corridors are cost-effective and resilient against market fluctuations. Social Sustainability involves the human dimension, ensuring that the benefits of corridors are distributed fairly and contribute positively to the communities they touch.

Technical and Operational Sustainability looks at the nuts and bolts of sustainable transport, emphasizing the importance of innovative technologies and resilient infrastructure. Governance and Policy emphasize the role of regulatory frameworks and policy development in steering corridors towards sustainable outcomes. Measurement, Monitoring, and Evaluation recognize the need for accountability through rigorous assessment of sustainability performance. Lastly, Integration and Systemic Approach emphasizes the holistic optimization of the transport system, recognizing the interconnectedness of all components involved.

Table 1. Description of taxonomy main components.

Component of Taxonomy	Brief Description
Environmental Sustainability	
Emissions Reduction	Strategies to lower greenhouse gases and air pollutants.
Energy Efficiency	Use of energy-efficient vehicles and infrastructure.
Renewable Energy Utilization	Incorporation of solar, wind, or biofuels.
Conservation Initiatives	Protection of biodiversity and prevention of ecological degradation.
Waste Management	Efficient disposal and recycling of waste products.
Water Management	Responsible use and treatment of water resources.
Economic Sustainability	
Cost-Effectiveness	Optimization of costs throughout the logistics chain.
Investment in Green Technologies	Funding for research and implementation of sustainable solutions.
Resource Optimization	Maximum utilization of materials and resources.
Sustainable Business Models	Incorporation of sustainability into business strategies.
Resilience to Market Fluctuations	Ability to adapt to economic changes while maintaining sustainability goals.
Social Sustainability	
Community Engagement	Inclusion of local communities in planning and decision making.
Fair Labor Practices	Ensuring safe working conditions and fair wages.
Equitable Access	Providing equal access to services offered by transport corridors.
Education and Training	Offering learning opportunities for skill development in sustainable practices.
Quality of Life Improvements	Enhancements that transport corridors bring to the surrounding areas.
Technical and Operational Sustainability	
Innovation and Technology	Deployment of cutting-edge technologies for sustainable transport operations.
Infrastructure Resilience	Building to withstand environmental and man-made challenges.
Sustainable Logistics	Implementing practices that minimize environmental impact throughout the supply chain.
Maintenance and Upkeep	Regular maintenance schedules that ensure longevity and efficiency of infrastructure and equipment.
Governance and Policy	
Regulatory Compliance	Adherence to international, national, and local regulations.
Policy Development	Creation of supportive policies for sustainable transport corridors.
Transparent Reporting	Public disclosure of sustainability practices and performance.
Stakeholder Collaboration	Partnerships among governments, businesses, and non-governmental organizations.
Measurement, Monitoring, and Evaluation	
Sustainability Indicators	Metrics developed to measure the sustainability performance.
Benchmarking	Comparing performance against industry standards or best practices.
Continuous Improvement	Ongoing efforts to enhance sustainability measures.
Feedback Mechanisms	Processes for incorporating stakeholder feedback into sustainability practices.
Integration and Systemic Approach	
Intermodal Synergies	Seamless connections between various modes of transport for efficiency.
System-Wide Optimization	Looking beyond individual components to optimize the entire system's sustainability.
Lifecycle Analysis	Assessment of environmental impact throughout the entire lifecycle of the corridor's components.

This taxonomy is not just a theoretical exercise but a practical toolkit. It facilitates the implementation of sustainability in a sector that has traditionally been dominated by concerns of speed and cost over those of the environment or social equity. By providing a detailed and organized framework, it assists in the transformation of international transport corridors into conduits for sustainable development, helping to meet today's needs without compromising the ability of future generations to meet their own.

This taxonomy of sustainability aspects offers a framework for assessing, planning, and implementing sustainable practices in international transport corridors. It recognizes the multidimensionality of sustainability, encompassing a balance between ecological integrity, economic security, and social equity, all crucial for the longevity and acceptance of these corridors.

The implementation of green transport corridors offers a plethora of benefits:

- Significant reduction in carbon emissions, air pollution, and noise, contributing to the fight against climate change.
- Lower operational costs through improved fuel efficiency and reduced congestion.
- Companies involved in sustainable practices often gain a competitive edge due to increased consumer demand for eco-friendly products.
- Diversification of transport modes and energy sources leads to more resilient supply chains.

Despite their benefits, green transport corridors face several challenges:

- The transition to green technologies and infrastructure requires substantial initial investment.
- The adoption of advanced technologies necessitates a skilled workforce and technological readiness.
- Inconsistent regulations across borders can impede the establishment of international green corridors.
- Effective implementation requires cooperation among various stakeholders, including governments, businesses, and communities.

The transformation of transport pathways into sustainable transport corridors requires a holistic approach that integrates environmental, social, and economic considerations. A tool for such a transformation, as well as assessing the effectiveness of the solutions used, can be a comprehensive modeling of the above-mentioned sustainability factors.

3.2. Modeling as a Tool for a Holistic Approach to Sustainable Transport Corridors Development

The dynamic and multifaceted nature of transforming traditional transport corridors into sustainable pathways demands tools that can capture the intricacies of the process and predict potential outcomes. Modeling stands out as an essential instrument in this regard. As a representative or simulation of a system, models can facilitate understanding, analysis, and prediction, making them invaluable for devising a holistic strategy for sustainable transport corridors.

The development of a comprehensive E-Net model for a sustainable transport corridor involves several key steps.

1. Network decomposition. The first step is to break down the transport corridor into constituent components. This includes identifying the main nodes (e.g., ports, warehouses, and terminals) as well as the links connecting them (e.g., rail lines, highways, and shipping routes).
2. Sustainability taxonomy. Based on the taxonomy of sustainability indicators presented earlier, the key performance metrics to be incorporated into the model across environmental, social, economic, and operational dimensions are determined.
3. E-Net construction:
    - Nodes are represented as sets of places and transitions encapsulating the activities and resources at each node.
    - Links are modeled as sequences of places and transitions capturing the flow of goods/vehicles and logistical activities.
    - Sustainability KPIs are integrated through additional places and transitions that represent metrics like emissions, energy efficiency, community impact, etc.
4. Parameterization. The E-Net components are parameterized by assigning time delays to transitions and tokens to places to quantitatively represent the dynamics of flows, processing times, and sustainability factors.
5. Simulation. The parameterized E-Net model is simulated using software tools to analyze the behavior under different conditions and parameter values.

6. Analysis. The simulation results are used to identify bottlenecks, resource utilization, delays, and other inefficiencies as well as quantify sustainability metrics.
7. Improvement. The insights from the model are used to formulate strategies to improve the efficiency and sustainability of the corridor, e.g., infrastructure changes, operational policies, and resource allocation.
8. Validation. The model is validated by comparing its performance predictions to actual observed data from the real corridor to test its accuracy.
9. Refinement. Based on validation results, the E-Net structure and parameters are refined iteratively to enhance the precision of its representation of the transport corridor.
10. Adaptation. The E-Net model provides a flexible template that can be adapted to different sections of the corridor or modified for other corridors.

The key contributions of this E-Net methodology are the following:

- Holistic integration of sustainability factors into transport corridor modeling using a standardized taxonomy.
- Quantification of sustainability KPIs within the dynamic simulation model.
- Visual modeling platform enabling easier understanding by stakeholders.
- Identification of inefficiencies and bottlenecks at granular levels.
- Ability to test various scenarios and strategies for improvements.
- Flexible framework that can be customized across transport corridors.
- Facilitates continuous improvement through ongoing model refinement.

This step-by-step methodology provides a systematic approach to develop an E-Net capable of providing actionable and quantitative insights into enhancing the sustainability of complex transport corridors.

3.2.1. Role of Modeling for the Green Transformation of Transport Corridors

Modeling is not just a tool but an integral component of a holistic approach to developing sustainable transport corridors. It simplifies complex systems, offers predictive insights, supports decision making, and fosters stakeholder engagement. As the world moves towards more sustainable solutions, harnessing the power of modeling will be crucial to ensure that transport corridors are not just efficient but also environmentally friendly, socially inclusive, and economically beneficial. The role of modeling in this context is presented in Table 2.

Table 2. Role of modeling in the analysis of transport corridors.

Direction of Analysis	Description
Comprehensive Understanding	• Modeling provides a visual representation of the entire transport system, making it easier to comprehend the relationships between different components—from infrastructure and energy sources to economic and social impacts. • Through models, various scenarios can be simulated, enabling stakeholders to understand potential outcomes based on different inputs or decisions.
Predictive Insights	• Using modeling, it is possible to predict the environmental, social, and economic impacts of specific corridor development strategies or technologies. • Models can highlight potential risks, be they ecological, financial, or societal, associated with different development pathways.
Decision Support	• Economic models can provide a clear picture of the costs associated with certain decisions compared to the potential benefits, guiding resource allocation. • Modeling can assist in identifying the most efficient and sustainable methods or technologies, ensuring optimal outcomes for investments.

Table 2. *Cont.*

Direction of Analysis	Description
Stakeholder Engagement	• Modern modeling tools often offer interactive platforms where stakeholders, from policymakers to the general public, can engage, explore different scenarios, and provide feedback. • Sharing models with the public can enhance transparency in decision-making processes, building trust among communities affected by corridor development.
Adaptive Management	• Models can integrate real-time data to continually update and refine predictions, establishing a feedback loop that allows for adaptive management of the corridor. • As external conditions change, such as shifts in global trade patterns or advancements in technology, models can re-evaluate scenarios to ensure the corridor remains sustainable and efficient.
Integration of Multi-disciplinary Data	• A model can seamlessly integrate data from various disciplines, from environmental science and engineering to sociology and economics, offering a truly holistic view of the corridor. • By using a shared model, experts from different fields can collaborate more effectively, ensuring that all aspects of sustainability are considered.
Future Preparedness	• Models can analyze current trends to project future developments, whether in terms of transportation demands, technological advancements, or environmental challenges. • By simulating potential future challenges, models can assist in building transport corridors that are resilient to changes and unforeseen events.

3.2.2. Key Performance Indicators for Sustainable International Transport Corridors: An Analytical Perspective

The evolution of international transport corridors in accordance with sustainability principles necessitates the inclusion of relevant Key Performance Indicators within their models. These indicators should encompass the broad spectrum of sustainability, namely, the environmental, social, and economic domains, providing quantifiable targets and benchmarks for the assessment of corridor performance. The main Key Performance Indicators that should be included in a sustainable international transport corridor modeling framework are identified in Table 3.

Table 3. KPIs for the modeling of sustainable transport corridors.

Group of KPI	KPI	Description of KPI
Environmental KPIs	Carbon Footprint	This KPI measures the total greenhouse gas emissions, particularly CO_2, associated with the corridor's operations.
	Energy Efficiency	The amount of energy required per unit of transport work done, considering both renewable and non-renewable sources.
	Emission Reduction	The extent to which strategies have successfully decreased emissions of NO_x, SOx, particulate matter, and other pollutants.
	Biodiversity Impact	An index to assess the impact of transport activities on local flora and fauna, including habitat disruption.
Social KPIs	Accessibility	The degree to which the corridor provides equitable access to transportation for diverse populations.
	Community Impact	Measurement of the corridor's impact on local communities, including economic displacement and effects on local businesses.
	Safety and Security	The frequency of accidents or security incidents related to the corridor's operations.
	Noise and Vibration	Monitoring the levels of noise and vibration caused by transport operations, affecting both humans and wildlife.

Table 3. *Cont.*

Group of KPI	KPI	Description of KPI
Economic KPIs	Cost Efficiency	The cost-effectiveness of the corridor in terms of construction, maintenance, and operation relative to the volume of goods transported.
	Trade Facilitation	The effectiveness of the corridor in enhancing trade, measured by the volume and value of goods transported.
	Economic Growth	The contribution of the corridor to regional and national economic growth, including job creation and GDP contribution.
	Return on Investment	The financial return on capital invested in the corridor's infrastructure and technology.
Integrated Sustainability KPIs	Sustainable Infrastructure Rating	A composite index reflecting the incorporation of sustainable materials and technologies in corridor infrastructure.
	Resilience and Adaptability	The corridor's ability to maintain functionality and recover quickly from various disruptions, whether economic, environmental, or social.
	Life Cycle Assessment	Evaluating the environmental impact of the corridor throughout its entire life cycle, from construction to decommissioning.
	Stakeholder Satisfaction	The level of satisfaction among all stakeholders, including users, local communities, and governmental bodies.

Most of the indicators presented in Table 3 are composite, covering a whole area of influencing factors. Detailing the indicators is beyond the limited scope of this article. But as an example, we can reveal the content of, for example, an indicator such as Sustainable Infrastructure Rating.

The selected KPIs reflect the nuances of different management levels. Strategic KPIs, such as carbon footprint and energy efficiency, focus on long-term sustainability goals. Operational KPIs, like safety and security measures, ensure the efficient daily functioning of the corridors.

The Sustainable Infrastructure Rating (SIR) serves as a composite index designed to evaluate the degree to which infrastructure projects, including international transport corridors, adhere to sustainability principles across their lifecycle. It aims to encapsulate a wide range of sustainability metrics into a singular, comprehensive score or rating system. The SIR is critical for investors, developers, policymakers, and other stakeholders to assess the sustainability profile of a transport corridor and to make informed decisions.

The detailed description of the key components and considerations that typically contribute to the Sustainable Infrastructure Rating is presented in Table 4.

The Sustainable Infrastructure Rating provides a quantitative and qualitative measure of a transport corridor's performance in sustainability. It serves as a critical tool for continuous improvement, providing benchmarks and targets for future developments. By adhering to the metrics set forth by the SIR, transport corridors can not only enhance their operational efficiency and cost-effectiveness but also demonstrate their commitment to global sustainability objectives.

The KPIs and sub-components of the SIR presented in Tables 3 and 4 are synthesized from established sustainability frameworks, including the UN Sustainable Development Goals [54], the GRI Standards for Sustainability Reporting [55], and ISO standards for sustainable infrastructure [56]. While not exhaustive, they aim to encompass a breadth of factors identified as vital considerations in the contemporary literature on sustainable transport infrastructure.

Table 4. Detailed description of the key components and considerations of SIR.

SIR Components	Description
Material and Resource Utilization	• The SIR considers the types of materials used in the construction of transport corridors, prioritizing the use of recycled, recyclable, and sustainably sourced materials. • It evaluates the efficiency of resource use, including the minimization of waste and the conservation of water and energy during construction and operation.
Energy Efficiency and Carbon Management	• This aspect of the SIR looks at the energy consumption patterns of the transport infrastructure, including the adoption of renewable energy sources. • The infrastructure's carbon footprint is critically assessed, taking into account both direct emissions from operations and indirect emissions from associated activities.
Ecosystem Conservation and Biodiversity	• The rating assesses measures taken to minimize the impact on natural habitats and biodiversity, including the preservation of existing ecosystems and the restoration of areas disturbed by construction. • It also evaluates the implementation of green infrastructure, such as green belts and wildlife crossings, to mitigate ecological disruptions.
Water Management	• SIR includes the analysis of the infrastructure's impact on local water resources, encompassing stormwater management systems and the treatment and reuse of wastewater.
Social and Community Engagement	• The rating system considers the level of engagement with local communities, ensuring that the development and operation of the corridor align with the social needs and values of the affected populations. • It also examines the project's contributions to local community development, such as improving accessibility and creating job opportunities.
Economic Viability and Lifecycle Costing	• The Sustainable Infrastructure Rating incorporates the economic assessment of the project, including the long-term economic benefits and cost savings resulting from sustainable practices. • Lifecycle costing evaluates the total costs associated with the development, maintenance, and operation of the infrastructure over its expected life.
Innovation and Adaptation	• The SIR values the integration of innovative technologies and practices that enhance the sustainability of the corridor. • It also assesses the corridor's design and operational adaptability to future changes, including climate resilience and flexibility for technology upgrades.
Compliance and Standards	• Compliance with international standards, local regulations, and best practices in sustainability is a critical component of the SIR. • The rating reviews the implementation of sustainability certifications and awards that the project may have received.

In terms of quantification, certain KPIs and SIR components lend themselves better to quantitative measurement and benchmarking. These include carbon footprint, energy efficiency, cost efficiency, trade facilitation, and various usage and efficiency ratios that can be numerically tracked over time. However, qualitative and descriptive assessments are equally important for capturing critical sustainability issues that are not readily quantified, such as biodiversity impact, community engagement, and policy frameworks in place. The overall SIR can be expressed as an aggregate score but should also highlight priority areas needing improvement based on a qualitative review. An effective framework relies on a judicious balance of quantitative metrics and qualitative evaluations tailored to the corridor context. To determine the values of indicators, for example, the methodology for the development of SRI can be used [57].

By integrating KPIs from Table 3 into the models of international transport corridors, policymakers and developers can effectively monitor and evaluate the sustainability of these critical pathways. These indicators provide a structured framework for continuous improvement and allow for the alignment of corridor development with international sustainability goals. Furthermore, they serve as a basis for transparent reporting and accountability, fostering trust and collaboration among stakeholders. The adoption of these KPIs is instrumental in transitioning towards transport corridors that are not just economically robust but are also environmentally conscious and socially responsible.

3.2.3. Objective Function of Modeling

Mathematically modeling an international transport corridor involves creating a quantitative representation of the various components and dynamics that define the operation and performance of the corridor. The goal of such modeling is typically to optimize specific aspects of the corridor's function, such as cost-efficiency, throughput, environmental impact, or a combination of multiple factors.

The main components of the mathematical model framework are the following:

- Network representation, which involves mapping the physical and logical structure of the transport corridor, including nodes (e.g., ports and terminals) and links (e.g., roads and railways).
- Flow models, which describe how goods, people, or vehicles move through the network, potentially using flow variables x_{ij} to quantify the movement on each link between points $i,\ j$.
- Capacity constraints, which ensure that the flow does not exceed the physical or operational capacities of the links or nodes.
- Time-dependent variables, which capture the dynamics of the system, such as varying demand, congestion levels, and service frequency over time.
- Cost functions, which calculate the costs associated with the flows, including infrastructure, operational, and external costs (e.g., environmental costs).
- Emission models, which estimate the emissions associated with transport activities, which are critical for assessing environmental impacts.
- Demand models, which predict the demand for transport services, which can be influenced by economic factors, service levels, and policy decisions.

The comprehensive mathematical model integrates the framework components into an optimization problem, where the objective is to minimize or maximize certain performance metrics subject to a set of constraints.

An objective function Z in the context of optimization is a mathematical expression that defines the goal of an optimization problem. It quantifies the corridor's performance by combining various factors such as cost, carbon emissions, travel time, and other relevant sustainability and efficiency metrics. In the sustainable transport corridor optimization scenario, the objective function has the next form:

$$Minimize\ Z = \alpha_1 C + \alpha_2 V + \alpha_3 E + \alpha_4 S + \alpha_4$$

where

C is the total cost associated with the transport corridor operations, including infrastructure, maintenance, logistics, etc.

V is the throughput, or the efficiency of the transport corridor in terms of goods/people moved.

E is the environmental impact, which is a function of the various sustainability KPIs as previously defined.

S represents the social impact, which may include factors like community displacement, employment, etc.

Q is the service quality, which could encompass factors like reliability, frequency, and speed of service.

$\alpha_i,\ i = 1, \ldots 5$ are the weights assigned to each of the terms, reflecting their relative importance in the decision-making process. These weights are often determined by policy priorities, stakeholder input, and strategic objectives.

Each term is further defined as follows:

$$C = \sum_{\forall i,j} \left(c_{ij} \cdot x_{ij} \right)$$

$$V = \sum_{\forall i,j} (v_{ij} \cdot x_{ij})$$

$$E = \sum_{\forall i,j} (e_{ij} \cdot x_{ij})$$

$$S = \sum_{\forall i,j} (s_{ij} \cdot x_{ij})$$

$$Q = \sum_{\forall i,j} (q_{ij} \cdot x_{ij})$$

where

c_{ij} is the cost per unit of transport on link ij.
v_{ij} is a measure of throughput or efficiency for link ij.
e_{ij} is the environmental impact for link ij, composed of the sustainability KPIs.
s_{ij} is the social impact for link ij.
q_{ij} is the service quality measure for link ij.
x_{ij} is the flow on link ij, which can be in terms of number of trips, volume of traffic, or quantity of goods transported.

This objective function is part of a larger optimization problem that would include a variety of constraints, such as the following:

- Flow conservation constraints (ensuring the movement through the network is consistent).
- Capacity constraints (not exceeding available infrastructure or service capacity).
- Time-dependent constraints (considering temporal variations in demand and supply).
- Environmental regulations (limiting emissions or other environmental impacts).
- Social considerations (addressing community needs and impacts).
- Policy and operational constraints (adhering to laws, standards, and strategic goals).

In practice, the objective function and the constraints need to be tailored to the specific context of the transport corridor being modeled. Real-world data, stakeholder input, and scenario analysis play crucial roles in defining the parameters and calibrating the model. The mathematical model's output then informs decision making regarding the design, operation, and optimization of the corridor to balance efficiency, sustainability, and social outcomes.

The challenge in solving such a model lies in the complexity of accurately quantifying each term and the inherent trade-offs between them.

For example, the environmental impact e in the context of sustainability within a transport corridor should indeed be aligned with the sustainability KPIs previously discussed. Let us correct the approach and ensure that the environmental impact reflects the broad spectrum of sustainability considerations that should be included in the mathematical model.

The sustainability KPIs previously mentioned can include the following:

- Emission levels of greenhouse gases.
- Levels of air and noise pollution.
- Energy consumption.
- Biodiversity and ecosystem impacts.
- Water resource management.
- Waste management.

Given these categories, the environmental impact e for a transport link i, j can be mathematically defined as a composite index of these sustainability KPIs, each normalized and weighted according to their relative importance and impact:

$$e_{ij} = w_1 \cdot GHG_{ij} + w_2 \cdot Pollution_{ij} + w_3 \cdot Energy_{ij} + w_4 \cdot EcoImpact_{ij} + w_5 \cdot Water_{ij} + w_6 \cdot Waste_{ij}$$

where

GHG_{ij} is a measure of greenhouse gas emissions normalized to a common scale.
$Pollution_{ij}$ is an index of air and noise pollution levels.
$Energy_{ij}$ represents the energy efficiency or consumption.
$EcoImpact_{ij}$ quantifies the impact on biodiversity and ecosystems.
$Water_{ij}$ captures impacts on water resources, both in terms of consumption and quality.

$Waste_{ij}$ reflects the effectiveness of waste management along the transport link.
w_i, $i = 1, \ldots 6$ are the weights assigned to each KPI, reflecting policy priorities or regulatory standards.

Similarly, other components of the objective function of modeling can be described in general form.

3.3. Petri Net-Based Models for International Transport Corridors

Modeling complex systems such as green transport corridors is a challenging task. Traditional models often fall short in capturing the multifaceted nature of sustainability. This is where Petri net-based models become invaluable. Their ability to model complex systems with multiple interacting components makes them particularly suited for designing and analyzing sustainable transport corridors. Petri nets, a mathematical modeling language used for the description and analysis of systems characterized by concurrent, asynchronous, distributed, parallel, nondeterministic, or stochastic activities, have emerged as a powerful tool for modeling international transport corridors [58].

Petri nets are composed of places, transitions, and tokens. Places represent conditions or states, transitions signify events that may change these conditions, and tokens are used to mark the places. The distribution of tokens over the places describes the state of the system. When all conditions for a particular transition are met (i.e., all the input places have the necessary tokens), the transition fires, consuming tokens from input places and producing tokens in output places, thus changing the state of the system.

3.4. Model Development: Constructing the E-Net Model for an International Transport Corridor

Petri net is a mathematical modeling language that is especially useful for building models of parallel, asynchronous, distributed, nondeterministic, and/or stochastic systems [59]. For the considered class of problems of modeling alternative transport routes and related parameters, Evaluation Petri nets, or E-Nets, which are an extension of Petri nets presented in [60], seem to be especially convenient.

The E-Net can be described by set of components:

$$N = (P, T, A, M)$$

where P is a set of places, T is a set of transitions, $A \subseteq (P \times T) \bigcup (T \times P)$ is a set of arcs, and M is an initial marking.

The development of an E-Net model for an international transport corridor involves several key steps:

1. Identification of components. The first step involves identifying the core components of the transport corridor, including nodes (e.g., ports, logistics centers, and stations) and transport routes (e.g., rail, road, and sea).
2. Modeling nodes and routes. Each node and route is modeled as a sub-net within the E-Net. Nodes are represented by a cluster of places and transitions, encapsulating the operations and processes occurring within the node (e.g., loading, unloading, and storage). Similarly, routes are modeled as sequences of places and transitions, representing the movement of goods and the activities along the route.
3. Incorporating time and cost. Time delays and cost values are assigned to transitions to reflect the duration and cost associated with each event. These attributes are crucial for simulating the operational dynamics and for evaluating the sustainability and efficiency of the transport corridor.
4. Establishing connectivity. The sub-nets corresponding to nodes and routes are interconnected through arcs, establishing the flow relations between them. This connectivity mirrors the physical and logistical linkages within the transport corridor.
5. Initial Marking and Simulation. The initial marking is set based on the initial conditions of the transport corridor (e.g., initial cargo at ports). The E-Net model is then

simulated to observe the flow of tokens, representing the movement of goods and the execution of operations within the corridor.

This mathematical framework offers a robust and nuanced representation of the transport corridor, enabling stakeholders to analyze its performance, identify areas for improvement, and make informed decisions towards achieving sustainable transport logistics.

3.5. The Elementary E-Net Model of Transport Corridor Chain

The elementary simplified E-Net model (Figure 2) streamlines the complexity of international transport corridors into three critical components: the start position (P_1), the transition (t_1), and the end position (P_2). P_1 represents the entry point into the transit country from the first country, t_1 embodies the entire transportation process within the transit country, and P_2 signifies the exit point towards the next country in the corridor. This abstraction allows for a focused analysis of the logistics performance within the transit country.

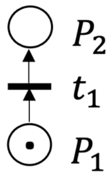

Figure 2. The elementary E-Net model of transport corridor chain.

4. Results

4.1. Case Study of Asia–Europe Transport Corridor Modeling

Let us look at an example of an international transport corridor.

Among the most sustainable transport connections between Europe and Central Asia, there are three land-based transport corridors described in [24]. One of them is the Trans-Caspian International Transport Route (Middle Corridor) which connects Asia and Europe via Kazakhstan and the Caspian Sea. Goods enter the Caucasus through the port of Baku, Azerbaijan, and continue to Georgia, from where two alternative routes can be taken before entering the EU via Bulgaria or Romania.

If cargo starting from Chengdu, a major city in Southwest China, must be transported to Europe (for example, Frankfurt, Germany), we can use the following route (Figure 3):

1. Chengdu, China—The journey begins here, with cargo being loaded and customs procedures being carried out before departure.
2. Xi’an, China—The cargo may pass through Xi’an, a key logistics hub in central China, for consolidation or onward transport.
3. Lanzhou, China—Another stop within China for cargo checks and possible route changes towards international borders.
4. Ürümqi, China—The last major Chinese city before exiting China. Here, cargo might undergo final checks and reorganization for international transit.
5. Khorgos, China/Kazakhstan Border—The cargo enters Kazakhstan through the Khorgos Gateway, a major dry port on the border. This is one of the significant border points where cargo undergoes customs and border clearance procedures.
6. Almaty, Kazakhstan—The largest city in Kazakhstan, serving as a significant regional logistics and transport hub.
7. Nur-Sultan, Kazakhstan—The capital city of Kazakhstan might be a checkpoint or transshipment point for further movement westward.
8. Aktobe, Kazakhstan—A city in Western Kazakhstan that might serve as a routing point for logistical operations moving toward Europe.
9. Atyrau, Kazakhstan—Near the Caspian Sea, cargo could be transferred for shipping across the Caspian if that route is preferred.
10. Aktau, Kazakhstan—This is a port city on the Caspian Sea where goods might be shipped across to Azerbaijan’s Baku or potentially routed through to the Caucasus.

11. Baku, Azerbaijan—From here, goods may transit through Azerbaijan, potentially using the Baku–Tbilisi–Kars railway.
12. Tbilisi, Georgia—Cargo can transit through Georgia towards the Black Sea for maritime transport or continue by rail.
13. Poti or Batumi, Georgia—Port cities on the Black Sea for potential shipping across to Romania's Constanta or Bulgaria's Varna ports.
14. Constanta, Romania—From the Black Sea port of Constanta, goods could be transported further into European networks.
15. Bucharest, Romania—As a major logistics hub in Southeast Europe, cargo might be processed through Bucharest before heading to the final destination.
16. Budapest, Hungary—The cargo enters the European Union and passes through another significant logistics and transportation center.
17. Vienna, Austria—Continuing west, the cargo moves through Austria, nearing its final destination.
18. Prague, Czech Republic—A central European logistics hub that could serve as a consolidation or distribution point for cargo before reaching the final destination.
19. Nuremberg, Germany—Before reaching the final city, cargo could go through Nuremberg, an important node in European transportation.
20. Final Destination: Frankfurt, Germany—The end of the corridor, where goods are finally distributed to their ultimate recipients.

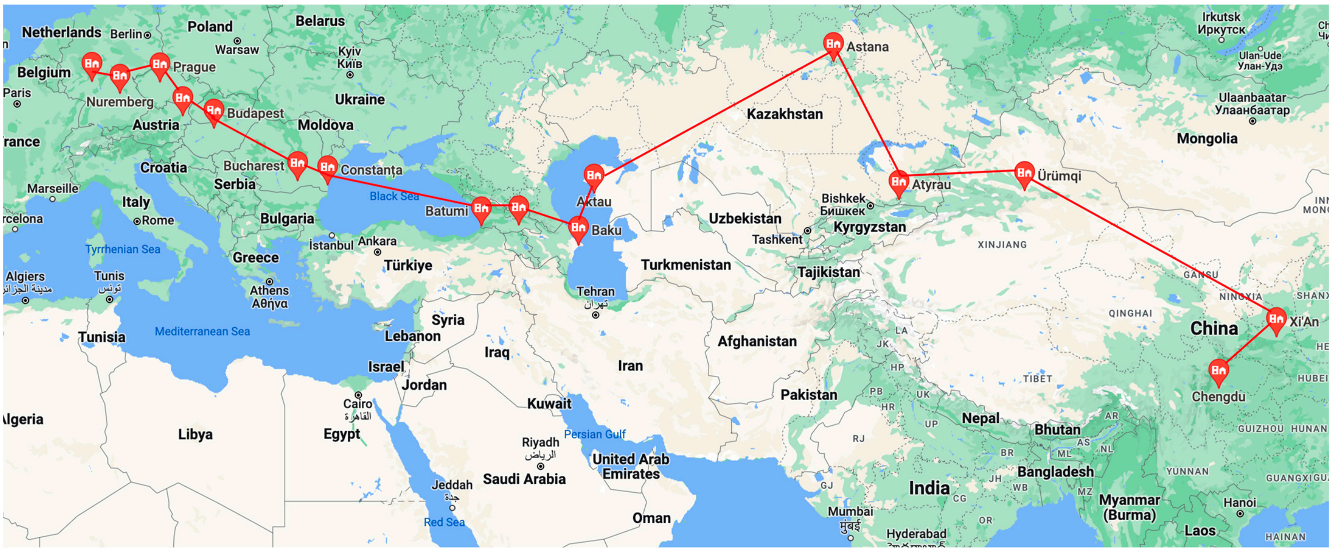

Figure 3. Case study of transport corridor for Asia–Europe.

This is a simplified representation and a theoretical route, and in practice, the path might vary based on multiple factors such as cargo type, transportation mode, geopolitical situations, and commercial considerations. It illustrates the complexity and length of such corridors, spanning multiple countries and involving various border crossings and transshipment points.

Using an elementary E-Net, the described transport corridor can be represented by the E-Net shown in Figure 4 at which the numbers of the E-network positions coincide with the numbers of the previously indicated transit points of the transport corridor.

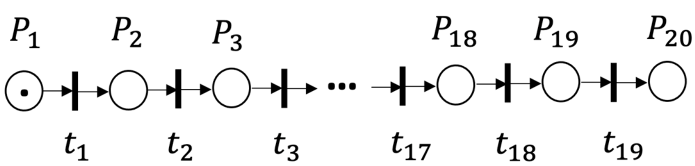

Figure 4. The model of transport corridor with elementary E-Nets.

4.2. The Transformation of a Simple E-Net into a Complex Model with Sustainability Factors

An elementary E-Net can model a national fragment of an international transport corridor, in which the transition delay is determined by an integral efficiency indicator. For a more accurate modeling of the national corridor, considering all the factors, both the transport component and sustainability factors, we can transform an elementary E-Net into a more complex one.

The transformation of a simple E-Net into a complex model with sustainability factors involves the inclusion of multiple layers of transitions and positions, each representing different sustainability KPIs. The methodology extends the classic Petri net structure to encompass a series of interconnected sub-nets, each tailored to assess specific KPIs related to environmental, social, and economic domains.

To incorporate the KPIs for a sustainable international transport corridor, an E-Net can be extended by an additional set of positions P_n and transitions t_m and different important factors of transportation via a country to form a more complex configuration that accounts for environmental, social, and economic factors.

Graphically, this E-Net would be quite intricate, with many layers and branches representing the multiple aspects of sustainability. Each layer could be distinguished to represent the environmental, social, and economic dimensions. This complex Petri net could be used to simulate various scenarios and optimize the performance of the corridor in a holistic way, truly integrating the concept of sustainability into every aspect of the transportation process.

In the context of an E-Net designed to reflect sustainability Key Performance Indicators for an international transport corridor, the full list of positions (P) and transitions (t) may be quite extensive, covering various aspects of environmental, social, and economic sustainability. In general, an international transport corridor may contain u national segments.

In this case, in accordance with the elementary network (Figure 2), each segment i $(i = 1,\ 2, \ldots, u)$ is represented by:

1. The start position P_i, signifying the entry point into the national segment.
2. The transition t_i, encapsulating the transportation processes within the segment i, also referred to as plane i.
3. The end position P_{i+1}, denoting the exit point of segment i and simultaneously the starting point for segment $i + 1$ in the corridor.

For each national segment i, when modeling the transportation processes using j sustainability indicators, the basic E-Net model can be extended into a more complex form (Figure 5). This extension is represented by a sequence of transitions and positions, $t_{ij},\ P_{ij}$, where

- i corresponds to the index of the national transport segment within the international corridor.
- j is the index of the sustainability indicator within the segment i, with $j = 1, 2, .. 23$.

Thus, the elementary E-Net $P_i \to t_i \to P_{i+1}$ for segment i of the corridor can be depicted as a sequence:

$$P_i \to t_{i1} \to P_{i1} \to t_{i2} \to P_{i2} \to \ldots \to t_{i23} \to P_{i23} \to P_{i+1}$$

where t_{ij} and P_{ij} are the transition and position states associated with the sustainability indicator j within the segment i of the transport corridor:

Environmental KPIs:

P_i: Entry Checkpoint Position (start of corridor)
t_{i1}: Environmental Compliance Transition (Carbon Footprint check)
P_{i1}: Energy Efficiency Position
t_{i2}: Emission Reduction Transition
P_{i2}: Biodiversity Impact Position
t_{i3}: Transition to Social KPIs

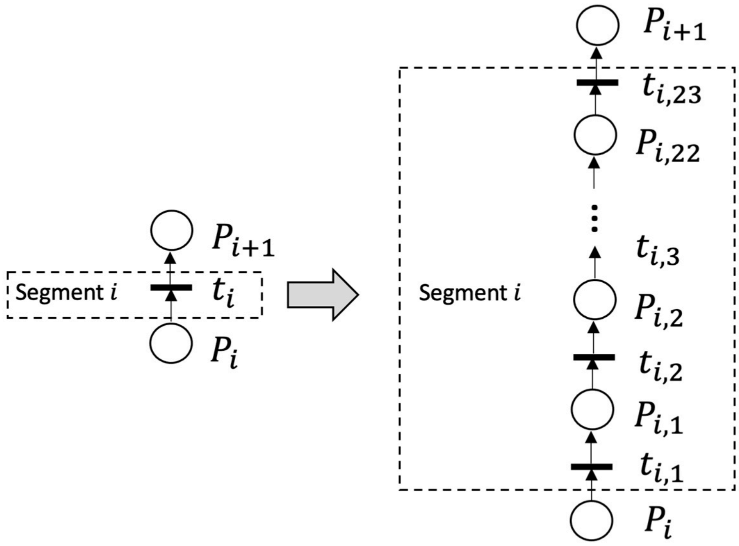

Figure 5. Transformation of elementary E-Net to complex E-Net.

Social KPIs:

P_{i3}: Social Accessibility Position
t_{i4}: Community Impact Assessment Transition
P_{i4}: Safety and Security Position
t_{i5}: Noise and Vibration Control Transition
P_{i5}: Social Checkpoint Position
t_{i6}: Transition to Economic KPIs

Economic KPIs:

P_{i6}: Economic Assessment Position
t_{i7}: Cost Efficiency Transition
P_{i7}: Trade Facilitation Position
t_{i8}: Economic Growth Transition
P_{i8}: Return on Investment (ROI) Position
t_{i9}: Transition to Integrated Sustainability KPIs

Integrated Sustainability KPIs:

P_{i9}: Sustainable Infrastructure Rating Position
t_{i10}: Resilience and Adaptability Transition
P_{i10}: Life Cycle Assessment Position
t_{i11}: Stakeholder Satisfaction Assessment Transition
P_{i11}: Integrated Sustainability Checkpoint Position
t_{i12}: Transition to Fundamental Transportation KPIs

Fundamental Transportation KPIs:

P_{i12}: Transportation Time Position
t_{i13}: Transit Time Transition
P_{i13}: Cost of Transportation Position
t_{i14}: Transportation Cost Transition
P_{i14}: Reliability Position
t_{i15}: Reliability Assessment Transition
P_{i15}: Load Factor Position
t_{i16}: Load Optimization Transition
P_{i16}: Inventory Position
t_{i17}: Inventory Throughput Transition
P_{i17}: Flexibility Position

t_{i18}: Flexibility Assessment Transition
P_{i18}: Multimodal Integration Position
t_{i19}: Multimodal Coordination Transition
P_{i19}: Customs and Clearance Position
t_{i20}: Customs Efficiency Transition
P_{i20}: Security Position
t_{i21}: Security Transition
P_{i21}: Infrastructure Quality Position
t_{i22}: Infrastructure Maintenance Transition
P_{i22}: Connectivity Position
t_{i23}: Network Connectivity Transition
P_{i23}: End of Journey Position in segment i (final destination with an assessment of overall transport quality) and at the same time start position of the next segment $i + 1$.

The actual transitions would involve processes and assessments related to each of the specific KPIs. Each position, in turn, would reflect the state of the transport process after the transition is made.

For example, the final position (P_{i24}) would be the summation of the corridor's adherence to all sustainability KPIs, signaling the readiness to exit the corridor and possibly enter the next phase of transport or the next segment of the international transport corridor.

Each component of the E-Net model is aligned with a specific management level. For instance, "Environmental Compliance Transition" is a strategic component aimed at overarching sustainability goals, whereas "Cost of Transportation Position" is operational, focusing on day-to-day efficiency and cost-effectiveness. The segmentation of the national segment into smaller sections and the definition of transportation nodes are tactical tasks. Conversely, the collection and analysis of data for each KPI and the assessment of section performance are operational activities, essential for the corridor's daily management.

The E-Net model includes specific components that represent both the physical and operational elements of transport corridors. For instance, "Environmental Compliance Transition" reflects operational decisions, while "Infrastructure Quality Position2 pertains to the physical infrastructure.

For a realistic E-Net, the sequence of transitions and positions might not be strictly linear as implied above. Some KPI assessments could occur in parallel. Furthermore, certain transitions might be conditional, only being necessary if previous positions reveal certain deficiencies or special conditions.

4.3. Expanded Model Framework

The methodology for constructing an E-Net model to represent a national segment of an international transport corridor can be adapted to provide greater granularity by applying the same principles to the individual sections connecting transportation nodes within the corridor. These nodes can include ports, customs checkpoints, warehouses, and distribution centers, each serving as a crucial juncture in the transportation network. By focusing on the discrete segments between these nodes, the model can capture the unique characteristics and performance metrics of each part of the corridor.

In this case, we can use the next modeling methodology.

1. The first step is to break down the national segment into smaller, manageable sections, each linking two successive transportation nodes. This segmentation aligns with the concept of microanalysis in logistics, where each part of the supply chain is analyzed for its specific operational dynamics. Precisely define each transportation node and the sections that connect them. This can include geographical boundaries, types of transport modalities used, and the nature of goods being transported.
2. For each section, identify local Key Performance Indicators (KPIs) that affect transportation efficiency and sustainability. These KPIs are more detailed than the national-level ones and can include local traffic conditions, infrastructure quality, and regional

customs efficiency. Determine relevant KPIs for each section based on its unique characteristics. For example, a section passing through an urban area may have different environmental and social KPIs compared to a rural section.
3. Each transition in a section would have a corresponding time delay function tailored to the specific characteristics and KPIs of the segment it represents. The complexity of these functions can vary depending on the variables at play. For each section, develop a time delay model that accounts for the throughput, efficiency, and sustainability of that specific segment. This could involve creating unique equations or adapting existing functions to local conditions.
4. Collect data for each KPI at the section level. Perform statistical analysis or apply machine learning techniques to determine the impact of each KPI on the section's performance and to parameterize the time delay functions.
5. Recognize and model the interdependencies between sections. Delays or efficiencies in one section can affect subsequent sections, and this ripple effect must be incorporated into the model.
6. Integrate these section-specific models into the larger national segment model. The total time delay and performance of the national segment are then the sum of the performances of the individual sections.
7. Recognize and model the interdependencies between sections. Delays or efficiencies in one section can affect subsequent sections, and this ripple effect must be incorporated into the model.
8. Set benchmarks for each section based on historical data, industry standards, or predictive simulations. Use these benchmarks to assess performance and identify areas for improvement.
9. Utilize the model for continuous improvement by regularly feeding back performance data into the model to refine and optimize each section's parameters.

By scaling the E-Net modeling approach down to individual sections of a national segment of an international transport corridor, stakeholders can gain a more detailed understanding of the dynamics at play. This granular approach facilitates targeted interventions to enhance efficiency, sustainability, and overall performance. It also allows for more agile and responsive management of the corridor, as each section can be optimized individually while still aligning with the corridor's broader operational objectives.

In constructing the E-Net model for a transport corridor, we give equal emphasis to modeling the physical infrastructure aspects, such as the quality and layout of transportation nodes, and the operational dynamics, including the management and efficiency of transport operations.

4.4. Mathematical Functions for Calculating Delay Time in Transitions of E-Nets

The operational efficiency of an international transport corridor is largely contingent upon the fluidity and reliability of its constituent transit operations. Within the architectural framework of Evaluation Petri nets, each transition serves as a critical juncture representing a variety of transport operations, from loading and unloading to travel and processing. The quantification of delay times at these transitions is essential for capturing the dynamic interplay between throughput and operational constraints within the network.

Delay times in E-Nets are not mere abstractions; they encapsulate a multitude of real-world variables including logistical efficiency, resource allocation, and adherence to timetables, as well as broader sustainability considerations. Given the complexity of these factors, the formulation of delay times must be both mathematically robust and intricately tied to the physical and operational realities of transport logistics.

The calculation of time delay for transitions in Evaluation Petri nets (E-Nets) can be approached through several mathematical functions that reflect the complexity and variability of operations within a transport corridor.

Below are the main functional dependencies that can be used to describe delays in E-Net transitions, as well as examples of their possible application.

1. Linear Functions

$T(x) = a + bx$, where T represents the time delay, x is the variable influencing the delay (e.g., volume of traffic or cargo), a is the fixed component of the time delay, and b is the coefficient that defines how much x contributes to the delay.

Use Case: Delay increases linearly with the amount of cargo processed at a terminal. Here, a could be a base processing time, and b represents the additional time needed per unit of cargo.

2. Exponential Functions

$T(x) = ae^{bx}$, where e is Euler's number, and the exponent bx reflects the rate at which the delay grows exponentially with respect to the influencing factor x.

Use Case: Modeling delays due to traffic congestion where delay grows exponentially with increasing traffic density, reflecting the non-linear escalation of congestion effects.

3. Logarithmic Functions

$T(x) = a + bln(x)$. This applies when the time delay increases at a decreasing rate with an increase in x.

Use Case: Represents the scenario where initial investments in sustainability (like green infrastructure) significantly reduce delays but with diminishing returns over time or investment scale.

4. Polynomial Functions

$T(x) = a + bx + cx^2 + \ldots + nx^k$. Each term represents a component of the delay influenced by the variable x raised to a certain power k, with n denoting the coefficient of the k-th term.

Use Case: Used when delay is influenced by multiple factors, such as operational efficiency and its squared term to model non-linear impacts on time delay.

5. Piecewise Functions

Defined by different expressions for different intervals of x:

$$T = \begin{cases} f_1(x)\ for\ 0 \leq x < x_1 \\ f_2(x)\ for\ x_1 \leq x < x_2 \\ \ldots \end{cases}$$

This approach can accommodate different operational regimes or rules within the transport corridor. Each function $f_i(x)$ corresponds to a specific regime of operation.

Use Case: Different delay formulas apply for different levels of traffic. For low traffic, one formula is used, while for high traffic, another formula is used to account for factors like an increased likelihood of accidents or delays.

6. Queuing Theory Functions

Based on queuing models like M/M/1 or M/G/1, the delay is calculated using the arrival rate λ and service rate μ of the system. For example, $T = 1/(\mu - \lambda)$ in a simple M/M/1 queue with a single server, exponential service times, and a Poisson arrival process.

Use Case: Useful in modeling the waiting time at customs or security checks in transport corridors, where λ is the arrival rate of vehicles and μ is the service rate.

7. Probabilistic and Stochastic Functions

These can be represented by a stochastic process $T(x)$, where T is a random variable with a distribution that depends on the factor x.

Use Case: Useful for modeling uncertain delays due to unpredictable events, like weather conditions or accidents, affecting transport corridor efficiency.

8. Empirical Functions

Derived from data, for example, through linear regression:

$$T(x_1,\ x_2,\ \ldots, x_n) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n$$

where $\beta_0, \beta_1, \ldots, \beta_n$ are coefficients estimated from the data, and $x_1, x_2, \ldots x_n$ are the independent variables.

Use Case: Used when there is a need to predict delays based on past trends and correlations, such as the relationship between freight volume and delays over time.

Each function must be chosen based on the characteristics of the system being modeled and the nature of the delays. These functions are then integrated into the E-Net to simulate and analyze the performance and efficiency of the modeled transport corridor. Incorporating these functions into an E-Net model allows for the simulation of time delays based on various operational factors, including but not limited to cargo volume, resource allocation, processing speeds, and regulatory checks.

The calculation of time delays in E-Nets has distinct implications at different levels. For operational decision making, understanding and managing traffic patterns is crucial. Strategically, assessing the long-term impacts of sustainability investments on time delays provides insights for future planning and policymaking.

Applied software tools [61] make it possible to carry out experiments for Petri nets of various configurations.

4.5. Advances and Impacts of the E-Net Modeling Approach

The E-Net model developed in this paper provides an original contribution that advances the quantitative modeling and analysis of sustainability factors in international transport corridors.

The model offers several key innovations:

- It integrates multiple sustainability KPIs into a single unified modeling framework, enabling holistic analysis. Prior models focused only on isolated metrics.
- It enables the dynamic simulation of sustainability factors and their complex interdependencies that impact transport efficiency. It provides predictive capabilities that are lacking in static models.
- It quantifies sustainability KPIs within the structure of the model. It allows for the direct computation of sustainability metrics.
- The visual modeling approach enhances the understanding of sustainability integration for stakeholders, providing the better communication of insights.

The proposed approach uses advanced modeling and analysis:

- The granular modeling of transport corridor components provides greater insights into where inefficiencies and issues arise, supporting targeted interventions.
- The flexible E-Net structure can be customized for different corridors and conditions, broadening applicability.
- The simulation capabilities support the evaluation of sustainability improvement scenarios, enabling ex-ante impact assessment.
- The model refinement and validation capabilities allow for incremental improvement in model accuracy, providing adaptation.

Both the integrated structure and the functional capabilities of the model facilitated by its Petri net foundations contribute innovative extensions to conventional modeling approaches.

5. Discussion

In the research paper under consideration, we present a methodological framework for sustainable transport corridor modeling using an E-Net (Evaluation Petri net) to understand and optimize a section of an international transport corridor. The discussion here elaborates on the practical implications, theoretical considerations, and potential for future research stemming from our E-Net model application.

5.1. Practical Implications

The E-Net model constructed for the corridor section provides a detailed schematic of the transport processes and allows for the identification of bottlenecks and inefficiencies. For practitioners in the field of logistics and transportation management, such a model is invaluable for several reasons:

- The model acts as a decision support tool, offering a visual and quantitative representation of each step in the transport process. This clarity assists managers in making informed decisions regarding resource allocation, process improvements, and investment in infrastructure.
- By highlighting specific delays at each transition point, the E-Net model directs attention to areas where operational efficiency can be improved, such as expediting customs procedures or streamlining toll collection.
- For policymakers, the model provides a framework for understanding the impact of regulatory decisions on transport efficiency. It can serve as a foundation for developing policies that balance security and regulatory compliance with the fluidity of goods movement.

5.2. Theoretical Considerations

The application of the E-Net model to a transport corridor introduces several theoretical considerations for the field of logistics and supply chain management:

- The model offers a structured approach to managing the complexity inherent in transport corridors. By decomposing the segment into discrete positions and transitions, the model simplifies the analysis and simulation of complex logistics networks.
- The use of time delay functions for each transition provides insights into the dynamic nature of logistics systems. These functions highlight how changes in one part of the corridor can have ripple effects throughout the entire transport network.
- E-Net modeling requires a blend of quantitative data (such as time measurements) and qualitative insights (like stakeholder feedback). This integration is critical for a holistic understanding of corridor performance.

Modeling international transport corridors using Petri nets, specifically E-Nets, can provide several advantages and disadvantages (Table 5). These reflect both the theoretical capabilities of Petri nets as a modeling tool and the practical realities of applying such models to complex, real-world systems.

While Petri nets offer a powerful method for modeling and analyzing international transport corridors, their application must be balanced with an understanding of the inherent complexity of such systems and the limitations of the tool itself. These advantages and disadvantages should be carefully weighed when considering Petri nets for practical use in this domain.

Future research directions for modeling international transport corridors with Petri net tools could encompass a wide range of topics, each aimed at addressing the current limitations and exploring new applications of Petri nets. Here are several potential areas for future research:

- Developing methods to integrate Petri nets with real-time data feeds to enhance the model's responsiveness and accuracy in reflecting current conditions.
- Using Petri nets in conjunction with machine learning algorithms or artificial intelligence to improve predictive capabilities and enable adaptive logistics planning.
- Combining Petri nets with other modeling approaches, such as agent-based modeling or system dynamics, to capture the complexity of transport corridors more effectively.
- Investigating optimization techniques within Petri net models to enhance the efficiency of transport corridors, reduce bottlenecks, and improve throughput.
- Developing interactive and user-friendly visualization tools for Petri net models to aid decision makers in understanding and utilizing the models for strategic planning.
- Exploring methodologies to handle the increasing complexity of Petri net models as they scale, possibly using modular or hierarchical Petri nets.

- Enhancing Petri net models to capture the nuances of intermodal transport, which involves multiple types of transportation modes and transfer points.
- Using Petri nets to assess the resilience of transport corridors and their vulnerability to disruptions from natural disasters, geopolitical events, or other risks.
- Creating standardized protocols for the application of Petri nets in transport corridor modeling to ensure the consistency and comparability of results.

Table 5. Advantages and disadvantages of E-Nets as modeling tool for transport corridors.

Advantages	Disadvantages
• Petri nets offer a clear visual representation of complex processes, making it easier to understand and communicate the flow of goods and information within international transport corridors. • E-Nets can model concurrent processes and synchronize multiple activities, which is crucial in transport logistics where many operations occur simultaneously. • Petri nets can simulate the dynamic behavior of systems, allowing for the prediction and analysis of system performance under different scenarios. • Through the use of tokens and firing rules, Petri nets can facilitate the quantitative analysis of the transportation process, including time delays, bottlenecks, and resource utilization. • They provide a formal mathematical framework, which can reduce ambiguity in the model's specifications and improve precision in the analysis. • Petri net models can be scaled to represent different levels of detail, from macro-level overviews of a transport corridor to micro-level views of individual processes. • The mathematical basis of Petri nets allows for the analysis and detection of deadlocks within the system, which is beneficial for improving operational efficiency.	• As the system becomes more complex, the Petri net can become large and unwieldy, making it difficult to manage and understand without sophisticated tools and expertise. • Understanding and using Petri nets effectively requires a certain level of expertise in discrete mathematics and system modeling, which can be a barrier for some practitioners. • For large and complex models, the computation required for analysis and simulation can be resource-intensive, necessitating powerful computing solutions. • While Petri nets are excellent for planning and analysis, they do not inherently incorporate real-time data, which can limit their applicability for on-the-fly decision making in dynamic environments. • Accurate modeling using Petri nets requires detailed and precise data, which can be challenging to obtain for all elements of an international transport corridor. • In simplifying real-world processes into places, transitions, and tokens, there is a risk of omitting important nuances, leading to an oversimplified model that may not capture all critical factors. • The structure of a Petri net is generally static, and dynamic changes in the network configuration can be challenging to model, such as temporary routes or changes in logistics strategies.

These directions not only present opportunities for advancing the state of the art in Petri net applications but also reflect broader trends in the fields of logistics, supply chain management, and sustainable development. By pursuing these research avenues, the application of Petri nets can continue to evolve and contribute to the optimization of international transport corridors.

5.3. Methodological Framework for Sustainable Transport Corridor Modeling

The core focus of this research centers around the development and application of a comprehensive methodological framework for modeling sustainable transport corridors.

The core component of research is a new methodological approach within the domain of transport corridor analysis. The utilization of Petri nets as a modeling tool represents a versatile approach to addressing the intricate dynamics of sustainable transport corridors. This methodological framework equips stakeholders with a potent tool for the early-stage analysis of transport corridors, allowing for the exploration of diverse scenarios and sustainability metrics.

Sustainability considerations are interwoven throughout the proposed methodology. It not only facilitates the modeling of transport corridors but also places sustainability at the forefront. The proposed framework empowers practitioners and policymakers to evaluate and optimize sustainability indicators, encompassing environmental, economic, and social dimensions.

The practical relevance of the proposed methodological framework is evident in its applicability to real-world transport corridor planning and decision making. Transport corridors serve as vital arteries of trade and connectivity, underscoring the significance of modeling and assessing their sustainability. This research bridges the divide between theoretical modeling and practical implementation, providing insights that can inform corridor development strategies, policy decisions, and investment choices. It recognizes the intricate interplay between transport corridors and broader socio-economic development goals.

It is crucial to recognize that while it is powerful, our framework may not provide exhaustive answers in all contexts. Limitations may arise from data availability, modeling assumptions, and the inherent complexity of transport systems. These serve as a foundation for further development and research oriented on future enhancements in the field.

Research offers a structured approach to assess sustainability indicators, providing a basis for informed choices that align with sustainability objectives. Methodology empowers stakeholders to navigate the complexities of modern transport corridors, where economic growth, environmental stewardship, and societal well-being converge.

6. Conclusions

This paper has presented a novel methodological framework for modeling sustainable transport corridors using Evaluation Petri nets (E-Nets). The rationale behind this approach is rooted in the growing relevance of sustainability considerations for modern transport infrastructure and recognition that traditional models often fall short in capturing the dynamics of green transport corridors.

The proposed framework puts forth a step-by-step methodology for constructing E-Net models that integrate sustainability indicators into the very fabric of the model structure. It demonstrates how E-Nets can be used to assess environmental, social, and economic dimensions through dedicated transitions and positions representing relevant KPIs. Mathematical functions for quantifying operational dynamics and time delays further enhance analytical capabilities.

Transport corridors are vital arteries of global trade, fostering economic development and interconnectivity between nations. The complexity of these corridors, compounded by the multitude of stakeholders and processes involved, necessitates sophisticated models to capture the intricacies of their operation. This study underpins the importance of recognizing and analyzing these corridors not just as logistical channels, but as ecosystems with profound economic, social, and environmental impacts.

Sustainability has emerged as an essential criterion in the evaluation and development of these corridors. The paper identifies key sustainability indicators, such as carbon footprint, energy efficiency, and socio-economic impacts, that must be integrated into the planning and operational phases of transport corridors. This holistic approach ensures that the corridors contribute positively to the regions they traverse while minimizing adverse effects.

To navigate the complexity of sustainability in transport corridors, this paper has presented the use of E-Nets as a modeling tool. E-Nets enable the visualization and analysis of the flow of goods, the identification of delays and inefficiencies, and the examination of sustainability factors in a quantifiable manner. By applying this model, stakeholders can gain insights into system behaviors, predict outcomes of changes, and formulate strategies for improvement.

The methodology demonstrated through the E-Net application involves decomposing the transport process into positions and transitions, with each representing a physical or procedural step. The methodology is underscored by its flexibility and adaptability, allowing for various levels of granularity in the model to match the required depth of analysis.

An essential feature of the E-Net modeling approach is its scalability. The study showed how the model could be expanded or contracted to cater to different segments of the transport corridor, providing a scalable tool that can be tailored to specific sections or encompass the entire corridor. This attribute makes E-Nets a versatile framework for both macro- and micro-level analysis.

The case study illuminated the practical application of the E-Net model to a national segment within an international transport corridor. This segment served as an elementary model for the broader dynamics at play in international transport. The model's ability to spotlight specific problem areas and predict the outcomes of potential solutions was showcased, demonstrating its value as a decision-making aid.

The discussion themes of sustainability, modeling, and the E-Net methodology are deeply interwoven. The E-Net model provides a bridge between the abstract principles of sustainability and the concrete realities of transport logistics. Through its adaptability, it can capture the multifaceted nature of transport corridors, reflecting economic, environmental, and social dimensions in a comprehensive framework.

The incorporation of E-Nets into the analysis of international transport corridors provides a significant advancement in our ability to understand and optimize these complex systems. The methodologies and case study presented underscore the importance of sustainability considerations in corridor management and offer a robust framework for future developments in this critical field.

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