Methodology of Transport Corridor Modeling Using Petri Nets

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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.

sustainable transport corridors | Petri nets | key sustainability indicators | green infrastructure

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.

2. 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.

3. 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.

4. 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.

5. 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.

6. 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.

7. 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.

8. 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.

9. 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.

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.

10. 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 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.

11. 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.

- 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).
- 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.
- 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.
- 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.
- Simulation. The parameterized E-Net model is simulated using software tools to analyze the behavior under different conditions and parameter values.
- Analysis. The simulation results are used to identify bottlenecks, resource utilization, delays, and other inefficiencies as well as quantify sustainability metrics.

- 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.
- Validation. The model is validated by comparing its performance predictions to actual observed data from the real corridor to test its accuracy.
- 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.
- Adaptation. The E-Net model provides a flexible template that can be adapted to different sections of the corridor or modified for other corridors.

12. 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.

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.

Petri net is a mathematical modeling language that is especially useful for building models of parallel, asynchronous, distributed, nondeterministic, and/or stochastic systems. For the considered class of problems of modeling alternative transport routes and related parameters, Evaluation Petri nets, or E-Nets 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, $A \subseteq (P \times T) \cup (T \times P)$ 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:

- 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).
- 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.

- 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.

- 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.

- 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.

13. 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.

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