Chapter 14

Deep Topological Intelligence for Sustainable Supply Chain Management:

A Structural Framework for Global Logistics Optimization

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ABSTRACT

The objective of this chapter is to develop Deep Topological Intelligence (DTI) as a structural framework for sustainable supply chain management, optimizing logistics while preserving viability, redundancy, and resilience. "Structural sustainability" is implemented by building a sea–air–rail–road logistics graph with cost, time, capacity, and emissions; simulating disruptions and targeted attacks; learning latent representations with autoencoders; and testing structural conservation with persistent homology, Betti curves, and Wasserstein distances. Contributions include a topology-informed digital-twin view (sustainability as persistence of form under perturbation), a reproducible workflow linking KPIs to homological indicators, a protocol that flags "efficient but fragile" AI designs, and a study of model capacity versus topological fidelity. Higher-capacity autoencoders preserve loop structure with minimal H_1 deformation (W≈0.054), while H_0 connectivity is more sensitive, revealing fragility missed by KPIs and supporting carbon-aware redesign without eroding redundancy.

1. INTRODUCTION: FROM THE FLOW OF GOODS TO STRUCTURAL KNOWLEDGE

1.1. The Transition Toward Sustainable and Resilient Logistics

This section analyzes the global transformation of supply chains, the environmental impact of multimodal transportation, and the urgent need for new models capable of balancing efficiency, resilience, and structural sustainability in an increasingly complex world. Figure 1 summarizes this section.

The global shift toward sustainable and resilient logistics arises from three converging pressures: the worldwide imperative for decarbonization, the growing exposure to systemic disruptions, and the structural complexity of global supply chains. Modern logistics networks now integrate maritime, air, rail, and road infrastructures into interdependent multimodal systems, where localized disturbances rapidly propagate through entire trade ecosystems. Recent crises ranging from pandemic disruptions and port congestion to climate-driven events and geopolitical instability have revealed that traditional optimization frameworks based solely on minimizing cost and time are no longer sufficient to ensure operational continuity or environmental accountability (Ivanov, 2020, 2023). Logistics is thus being reconceptualized as a practical system whose performance depends on its capacity to absorb shocks, reconfigure flows, and maintain connectivity under stress. Current research and policy agendas emphasize low-carbon corridors, digitalized border

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