Physical AI as a Governance Layer in Sustainable Supply Chains: Rethinking Accountability and Operational Autonomy

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Abstract

This paper conceptualises physical AI as a distinct governance layer within sustainable supply chains. As AI becomes embedded in robotics, sensors, computer vision, and edge control systems, operational decisions regarding material flows are increasingly executed autonomously and in real time. The research question explores how this rise in operational autonomy reshapes accountability structures and sustainability governance in supply chains. The aim is to move beyond efficiency-focused digital transformation narratives and to analyse physical AI as an organisational and systemic governance mechanism. The study adopts a conceptual and theory-building approach, integrating insights from supply chain governance, sustainability management, and AI governance research. It develops a governance-layer framework that explains how increasing algorithmic autonomy alters decision visibility, responsibility allocation, and the measurement of environmental performance. Three structural tensions are identified: operational autonomy versus managerial accountability, data-driven optimisation versus environmental externalities, and network-level efficiency versus local sustainability impacts. The findings suggest that physical AI can strengthen resilience and resource coordination in sustainable supply chains, yet it simultaneously creates accountability gaps when sustainability criteria are not embedded within algorithmic architectures. The paper contributes by linking sustainable supply chain governance with AI governance and by clarifying how physical AI transforms managerial control. For organisations and policymakers, the results highlight the need to integrate sustainability metrics directly into autonomous decision systems. The conceptual nature of the study is a limitation; further empirical research should test the governance-layer framework across industries.

Keywords: physical AI; governance layer; sustainable supply chains; operational autonomy; accountability; AI governance.