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From competing to complementary: Digital engineering ecosystems as net zero enablers

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1. INTRODUCTION

Organizations pursuing net zero goals face a paradox: achieving carbon neutrality across all emission scopes while maintaining competitiveness and growth (Erbetta et al., 2023). Net zero involves accounting for emissions in three categories: Scope 1 (direct emissions), Scope 2 (indirect emissions from purchased energy), and Scope 3 (other indirect emissions in the value chain) (Abili & Hemeda, 2023). It also requires active carbon removal, not just avoiding emissions or buying offsets. Traditional approaches create trade-offs between carbon neutrality, performance, and cost, treating these as competing rather than complementary goals. Achieving net zero demands systemic changes across product lifecycles and supply chains, embedding sustainability principles deeply. Current organizational capability, based on "build-test" approaches, are insufficient for future integrated solutions. Digital Engineering (DE) offers a new approach to reconcile these objectives. DE integrates data and models across business areas, enabling optimization through the integration of previously siloed systems and processes. Shifting from document-centric to model-based approaches is crucial for embedding sustainability throughout product lifecycles (Cai et al., 2023). This work synthesizes current understanding and practical experience to propose essential DE ecosystems capabilities for net zero transformation. It offers conceptual contributions to academic discourse and industry practice, along with practical implementation pathways addressing technical and organizational transformation requirements.

2. ANALYSIS AND FINDINGS

To understand how DE can resolve the net zero paradox, it's essential to examine the foundational tenets that define its effective implementation. DE is built on five core tenets that provide the infrastructure for a systematic transformation towards net zero. These principles help transcend traditional siloed approaches, fostering integrated ecosystems capable of handling the complexities of comprehensive carbon management.

First, organizations must formulate the development, integration, and use of models as the primary means of information exchange, moving away from document-centric approaches. This includes methodology such as Model-Based Systems Engineering (MBSE) which focuses on creating and exploiting digital system models as the primary means of information exchange, feedback, and requirements management. Second, they must establish a persistent and authoritative source of truth (ASOT) that provides consistent, reliable data across all organizational functions. The ASOT serves as the single, definitive source of information to mitigate risks of relying on outdated, inconsistent, or inaccurate data. Third, organizations need to adopt a reliable approach to incorporate technological innovations, ensuring that sustainability advances can be rapidly integrated into existing systems. Fourth, establishing a consolidated and collaborative infrastructure environment becomes essential, encompassing methods, processes, tools, hardware, software, networks, and security frameworks that enables seamless integration. Finally, the transformation of culture and workforce ensures that human capabilities align with the technological ecosystem (Tao et al., 2024).

DE influences multiple organizational areas critical to achieving net zero. It fosters green revenue through sustainable business models and reduces resource use via smart manufacturing and IoT. Digital twins allow for pre-implementation optimization, while operational improvements stem from decision optimization, machine learning, and circular processes. Workforce capabilities are enhanced through efficiency and knowledge management, and digital threads ensure sustainability insights guide lifecycle decisions. Within this broader DE framework, specific capabilities serve as the primary enablers for net zero transformation. For instance, Infrastructure as Code enables automated, efficient resource provisioning and management, eliminating waste through precise resource allocation and consistent deployment practices (Cao et al., 2025). The ASOT provides the data foundation essential for comprehensive carbon management. Predictive maintenance capabilities leverage tools such as Digital Twins to optimize equipment performance while reducing waste and energy consumption. Smart testing capabilities reduce the need for physical prototypes through the utilization of Modeling and

Simulation methodologies, significantly decreasing material and energy consumption associated with traditional development approaches. Automation and integration capabilities work together to minimize resource consumption while connection siloed systems through digital threads. This enables holistic management that capture complex interdependencies across the enterprise and value chain partners. These capabilities combine to create digital drivers that enable systematic transformation from reactive compliance to proactive net zero supporting strategies.

For DE to fulfill its potential as a net zero enabler, stakeholders across research, industry, and policy domains must address six critical success factors that determine whether DE implementations deliver genuine sustainability transformation (Sun & Ahmed, 2024; Taghikhah et al., 2025; Xiao, n.d.).

1. **System integration and digital ecosystem optimization:** Organizations must prioritize tool integration over proliferation to build efficient DE ecosystems, avoiding fragmented toolchains that create data silos undermining holistic emission management.
2. **Insight-Driven DE implementation:** DE initiatives must be insight-driven rather than technology-driven, extracting actionable intelligence from integrated data to generate measurable insights guiding carbon reduction strategies.
3. **Regulatory and standards compliance:** DE applications must align with environmental regulations and carbon accounting standards from outset, providing credibility while adapting to evolving frameworks without complete redesigns.
4. **Legacy system integration and interoperability:** DE solutions must integrate seamlessly with existing organizational systems to achieve widespread adoption, avoid operational disruptions, and capture comprehensive data for carbon management.
5. **Business case development and value communication:** Stakeholders must develop clear communication strategies demonstrating both financial and environmental returns, showing how DE enables optimization across competing objectives rather than trade-offs.
6. **Organizational capability development:** Organizations must implement comprehensive workforce development programs building DE competencies, requiring human expertise to interpret insights and manage technology-organizational interactions combining technical and sustainability knowledge.

3. Conclusion

DE represents a fundamental shift in approaching net zero, moving beyond trade-offs between environmental responsibility and operational excellence. Realizing this potential requires deliberate attention to six critical success factors, making DE ecosystems essential infrastructure for comprehensive carbon neutrality.

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