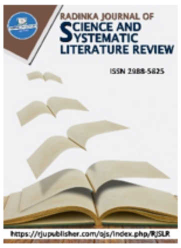

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The Role of Computer Simulation Impact for Sustainable Development in Engineering Experiments: Mini Review

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Abstract

Sustainable development has become a foundational principle in modern engineering research and practice. Conventional physical experiments frequently require considerable resource utilization, produce waste, and demand substantial time, thereby presenting obstacles to environmental objectives. This paper aims to evaluate the impact of computer-based simulations as a transformative approach to engineering experiments, specifically examining how they align with sustainability goals compared to conventional methods. This study employs a mini-review methodology, synthesizing data from various case studies across engineering disciplines. The analysis focuses on three primary sustainability metrics: resource efficiency, environmental impact reduction, and temporal optimization. The findings demonstrate that computer simulations drastically reduce the carbon footprint of research by minimizing the need for physical prototypes and hazardous materials. Furthermore, simulations allow for rapid iterative testing, which fosters innovation while ensuring high experimental rigor. Case studies show that integrating simulation tools can lead to a significant decrease in material waste up to 60-80% in certain manufacturing and structural testing scenarios. Conclusion: This study concludes that computer-based simulations are not merely a technical convenience but a critical driver for sustainable development in engineering. By maintaining experimental scrupulousness while enhancing efficiency, simulations provide a viable pathway for future-proof engineering practices that balance technological progress with environmental responsibility.

Keywords: Computer-simulation, sustainable-development, physical-experiments, carbon-footprints, renewable-energy.

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Introduction

In the contemporary engineering landscape, sustainability has emerged as an overarching goal, aiming to balance rapid technological advancement with ecological preservation and societal well-being (Ogunmodede et al., 2021). Traditional engineering experiments have historically relied on physical methodologies, which necessitate the intensive use of actual resources. However, these conventional approaches often lead to significant material waste, high energy consumption, and extensive time requirements. While physical testing remains a cornerstone of validation, the escalating global resource crisis demands a paradigm shift toward more sustainable experimental frameworks.

Computer simulations have revolutionized this domain by providing a virtual platform for studying, testing, and analyzing complex engineering designs and processes. Compared to traditional methodologies, simulations offer superior agility and a more robust response to resource scarcity. For example, resource efficiency is significantly enhanced as simulations eliminate the need for multiple physical prototypes, while protecting raw materials and reducing industrial waste (Commission on Environment, 1987). A descriptive example is Finite Element Analysis (FEA), which allows engineers to predict structural performance with high fidelity without the environmental cost of constructing physical models. Similarly, in additive manufacturing, simulations optimize material deposition, drastically reducing waste during prototyping stages.

Furthermore, simulation tools offer a profound reduction in environmental impact. By decreasing energy consumption and the greenhouse gas emissions associated with large-scale traditional setups, simulations directly lower the carbon footprint of research (Filonchyk et al., 2024). In the automotive industry, for example, aerodynamic simulations facilitate the design of fuel-efficient vehicles, indirectly contributing to long-term emission reductions. Beyond environmental benefits, cost-effectiveness and safety remain primary drivers. Conducting simulations are often more economically feasible than developing high-cost prototypes in sectors such as aerospace and defense (David Müzel et al., 2020). Moreover, in hazardous fields like nuclear and chemical engineering, simulations allow for the exploration of extreme conditions without endangering human lives or property (Baniassadi et al., 2018). Most existing studies treat simulation as a tool for efficiency rather than a strategic pillar for sustainability. The novelty of this mini-review lies in its comprehensive synthesis of cross-disciplinary case studies to demonstrate that computer simulation is not merely a technical alternative but a foundational requirement for "Scrupulous Engineering" a method that maintains rigorous experimental standards while achieving near-zero physical waste. This paper bridges the gap between digital precision and ecological responsibility, providing a roadmap for integrating virtual experimentation into sustainable development policies.

Methodology

This study employs a systematic mini-review approach to synthesize current knowledge about the role of computer simulations in promoting sustainable engineering practices. The methodology is structured into three main phases: literature identification, selection based on sustainability criteria, and thematic analysis.

Search strategy and data sources

A comprehensive search was conducted across prominent academic databases, including ScienceDirect, IEEE Xplore, SpringerLink, and Google Scholar. The search focused on peerreviewed articles, conference proceedings, and technical reports published predominantly within the last decade to ensure the inclusion of contemporary technological advances. The primary keywords used in various combinations include "Computer simulation" "Sustainable development in engineering" "Resource efficiency" "Environmental impact of experiments" "Finite Element Analysis (FEA) sustainability" "Virtual prototyping."

Inclusion and exclusion criteria

To maintain the focus of the review, specific criteria were applied to the retrieved literature:

- Inclusion Criteria: Studies that explicitly compare physical experimentation with computer-based simulation; research highlighting measurable reductions in material, energy, or time; and case studies involving industries such as automotive, aerospace, chemical, and manufacturing.
- Exclusion Criteria: Papers focus solely on simulation software development without ecological or resource-related analysis, and studies not available in English.

Data analysis and synthesis

The selected literature was analyzed using a thematic synthesis approach. Data were extracted and categorized into four sustainability-driven themes:

- Material Reduction: Analyzing how virtual models replace physical prototypes.
- Energy and Emissions: Evaluating the carbon footprint reduction from shifted experimental paradigms.
- Risk and Safety: Assessing simulation's role in dangerous experimental scenarios.
- Economic Viability: Comparing the cost-benefit ratio of virtual vs. physical setups.

Finally, the findings were cross-referenced to identify common patterns and "gaps" in the current integration of simulation tools within sustainable development frameworks. This structured synthesis ensures that the conclusions drawn are based on a rigorous evaluation of diverse engineering disciplines.

Result and Discussion

Transformative impact across engineering disciplines

The synthesis of current literature reveals that the integration of computer-based simulations is not merely a technical aid but a catalyst for a paradigm shift in engineering experimentation.

1. Renewable energy and aerodynamics: In renewable energy systems, simulations have revolutionized the design and optimization of wind turbines and solar panels. By using predictive modeling, engineers can simulate various wind speeds and structural loads without the need for large-scale physical prototypes (Yu et al., 2023). This implementation significantly reduces costs, development time, and material consumption (Ogunmodede et al., 2021). For example, aerodynamic simulations facilitate the identification of optimal blade designs, directly enhancing energy output efficiency over the turbine's operational lifespan.
2. Civil engineering and building information modeling (BIM): In civil engineering, virtual infrastructure modeling has minimized the risks of structural failure. The implementation of Building Information Modeling (BIM) allows for comprehensive data integration, from material selection to life-cycle environmental impact analysis (Ead & AbouRizk, 2024). Engineers can test structural integrity against seismic loads or extreme weather conditions in a virtual environment, significantly reducing construction waste caused by physical design errors.
3. Biomedical and aerospace applications: In biomedical engineering, biomechanical simulations of artificial joints ensure that designs meet strict durability standards before fabrication begins, improving patient outcomes while reducing medical material waste

(Malvè, 2023). Meanwhile, the aerospace sector leverages Computational Fluid Dynamics (CFD) to simulate airflow and thermal dynamics. This reduces reliance on expensive, energy-intensive wind tunnel experiments, accelerating the "green innovation" cycle in the aviation industry (Allerton, 2010).

Alignment with United Nations Sustainable Development Goals (SDGs)

This study identifies a strong correlation between simulation capabilities and the achievement of the United Nations Sustainable Development Goals (SDGs) (UN, 2015):

1. SDG 7 (Affordable and Clean Energy): Computer simulations support the design of smart energy systems capable of integrating fluctuating renewable sources into national grids, improving the reliability and efficiency of energy distribution (Lu et al., 2020).
2. SDG 9 (Industry, Innovation, and Infrastructure): Simulations facilitate innovation through rapid prototyping. By modeling the impacts of natural disasters, such as earthquakes or floods, on infrastructure designs, industries can develop more resilient and long-term sustainable structures (Southwick et al., 2021).

3. SDG 12 (Responsible Consumption and Production): The use of Digital Twin technology enables real-time monitoring of production lines in a virtual environment. This helps optimize energy use and minimize machine downtime, effectively reducing resource exhaustion and waste (Rohmah, 2024).

Comparative analysis: Virtual vs. Physical paradigms

Based on the data synthesis, the comparison between virtual and physical experiments can be categorized into several key performance metrics:

1. Material utilization: Traditional physical experiments involve iterative prototype production, which often results in significant industrial waste (Lian et al., 2020). Conversely, simulations allow for infinite iterations with zero physical resource consumption.
2. Time efficiency: Simulations enable parallel testing—where multiple scenarios are tested simultaneously drastically compressing experimental timelines compared to the sequential and rigid nature of physical setups.
3. Data Insights and Scalability: Computer simulations provide high-precision numerical data and uncover hidden patterns that are often undetectable through limited physical data collection. Furthermore, virtual scaling allows for testing at levels of complexity that would be impossible to replicate in a physical laboratory.

Challenges, Limitations, and Strategic Future Directions

Despite the clear advantages, the effectiveness of simulation faces fundamental challenges. The accuracy of results remains heavily dependent on the quality of input data and the robustness of the computational models used (Nazari & Matusiak, 2024). Certain highly complex physical phenomena cannot yet be fully replicated virtually, necessitating occasional physical validation. Furthermore, the computational cost of running high-fidelity simulations can be a barrier for smaller organizations and resource-constrained projects (Mundu et al., 2024). Looking ahead, the integration of Artificial Intelligence (AI) is predicted to enhance the predictive capabilities of simulation software and optimize accuracy through machine learning (Fachada & David, 2024). Promoting specialized education and training for engineers is also crucial, as advanced simulation variants require high computer literacy to be effectively utilized for sustainable development goals.

Conclusion

Despite their foundational nature, traditional engineering experiments are increasingly under scrutiny due to their intensive resource consumption, high environmental footprint, and lengthy development cycles. In an era where ecological preservation is paramount, the engineering sector requires a paradigm shift toward more sustainable research methodologies. This study seeks to assess the transformative function of computer-based simulations as a sustainable substitute for physical experimentation, with particular emphasis on their congruence with global sustainability objectives. The synthesis of various engineering disciplines from aerospace and civil engineering to biomedical and renewable energy demonstrates that simulations drastically improve resource efficiency. By replacing physical prototypes with high-fidelity virtual models, simulations reduce material waste by significant margins and minimize the carbon emissions associated with energy-intensive laboratory setups. Furthermore, technologies such as digital twins and computational fluid dynamics (CFD) provide profound data insights and parallel testing capabilities that are unattainable through conventional methods. It is concluded that computer-based simulations are essential drivers for achieving the United Nations Sustainable Development Goals (SDGs 7, 9, 12, and 13). They represent a "non-destructive" approach to engineering that harmonizes technological innovation with environmental stewardship. These findings imply that integrating simulation tools into early-stage engineering research is no longer an option but a necessity for sustainable development. This shift allows for "Scrupulous Engineering," where rigorous standards are maintained while achieving near-zero physical waste. However, the study acknowledges that the quality of input data and the maturity of computational models inherently limit the accuracy of simulations. Additionally, the high cost of specialized software and hardware remains a barrier for small-scale organizations and developing regions. Future studies should explore the synergy between Artificial Intelligence (AI) and simulation to enhance predictive accuracy and automate optimization. Moreover, research into open-source simulation platforms is crucial to democratize access to these sustainable tools, ensuring that the benefits of virtual experimentation are accessible to the global engineering community.

Conflicts of Interest

The authors declare no conflict of interest.

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Author contribution

Shen Hosan: conceptualization, methodology, and validation; **Hasith Perera**: formal analysis and investigation; **Vimukthi Vithanage** and **Dasith Wijesekara**: resources and data curation; **Anjula Kelum**: original draft writing; **Anjula Kelum** and **Kaveenga Koswattage**: review and editing, visualization. All authors have read and approved the final manuscript.

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