Reimagining Engineering Education through the Lens of Complexity Science: A Systems Approach to Embedding the UN SDGs

Smitha Maria Dsouza [1] and Poornesh M[2]

[1]*Department of Chemistry, St Joseph Engineering College, Mangaluru*
[2]*Department of Mechanical Engineering, St Joseph Engineering College, Mangaluru*

**Email: poorneshsjec@gmail.com*

Abstract

Engineering education is at a pivotal juncture, faced with the urgent need to respond to complex global challenges as articulated in the United Nations Sustainable Development Goals (UN SDGs). Traditional curricula, often grounded in linear and reductionist models, are insufficient to prepare students for the dynamic, interconnected systems they will encounter in professional practice. This article explores how complexity science and systems thinking can serve as transformative lenses for restructuring engineering education. By embedding the SDGs into course design, project work, and assessment practices, institutions can cultivate engineers who are not only technically competent but also ethically grounded and systemically aware. We propose a curriculum model that integrates interdisciplinary learning, project-based pedagogy, and stakeholder engagement, supported by institutional and faculty development. The article emphasizes the importance of treating SDGs not as ancillary topics but as integral design constraints and educational drivers. This reimagined approach aligns engineering education with its deeper purpose: to co-create sustainable, equitable solutions for a complex world.

Keywords: *Complexity science, Systems thinking, Engineering education reform, Sustainable Development Goals (SDGs), Curriculum innovation*

1. Introduction

Engineering education has historically been rooted in a paradigm of reductionism—dissecting systems into discrete parts, optimizing performance within boundaries, and prioritizing technical precision above all else [1], [2]. While this approach has driven remarkable technological advancements, it often falls short in equipping engineers to confront the complex, interconnected challenges of the 21st century. Climate change, clean energy transitions, sustainable urbanization, and global inequality are not problems that yield to narrowly defined, linear solutions [3], [4]. They require systems-level thinking, ethical reasoning, and a capacity to work across disciplines and stakeholder perspectives.

These very challenges are encapsulated in the United Nations Sustainable Development Goals (UN SDGs), a comprehensive global agenda that demands innovative engineering solutions that are socially inclusive, environmentally sound, and economically viable [5], [6]. Yet, in most engineering curricula, the SDGs are introduced—if at all—as peripheral themes, elective modules, or CSR-related content. The result is a disconnection between the way engineers are educated and the kind of thinking required to advance sustainable development [7].

At the same time, a promising paradigm is emerging from fields as diverse as ecology, organizational theory, and complex adaptive systems: Complexity Science. Its core principles—nonlinearity, emergence, feedback loops, and co-evolution—resonate deeply with the nature of the problems modern engineers face [8]. When applied to education, systems thinking, a practical lens of complexity science, offers a transformative way to design engineering programs that cultivate holistic problem-solvers rather than isolated specialists [9].

This paper explores how engineering education can be reimagined through the lens of complexity science. It proposes a curriculum framework that places the SDGs at the heart of engineering formation—not merely as content but as complex systems challenges. The goal is to provide a conceptual foundation for rethinking pedagogy, curriculum design, and institutional culture in a way that prepares engineers not just to solve problems—but to understand the systems in which those problems reside.Congratulations! Your paper has been accepted for journal publication. Please follow the steps outlined below when submitting your final draft to the GEDRAG ORGANISATIE Press. These guidelines include complete descriptions of the fonts, spacing, and related information for producing your proceedings manuscripts. Please follow them and if you have any questions, direct them to the production editor in charge of your journal at the GEDRAG ORGANISATIE.

2. Theoretical Foundations: Complexity Science & Systems Thinking

At the heart of the transformation in engineering education lies a fundamental shift in how we understand systems and problem-solving. Complexity Science provides a theoretical foundation for this shift, offering a lens through which the messy, interconnected, and dynamic nature of real-world challenges can be better understood and addressed [10]. Unlike traditional science, which often seeks to isolate variables and control systems, complexity science embraces uncertainty, emergence, and feedback—characteristics intrinsic to most sociotechnical problems.

Complex systems are marked by nonlinear relationships, where small inputs can lead to disproportionate effects, and outcomes are often unpredictable due to interdependencies among components [11]. Examples in engineering include transportation networks, energy grids, and climate systems. These are not merely complicated systems with many parts, but complex adaptive systems that evolve, self-organize, and interact with their environment. In such systems, the behavior of the whole cannot be fully understood by analyzing parts in isolation.

Systems Thinking, as a practical application of complexity science, equips learners with tools to see these interconnections [12], [13]. It emphasizes holistic thinking, causal loops, feedback structures, time delays, and leverage points—key concepts that are particularly useful in engineering contexts involving sustainability, resilience, and innovation. For example, systems thinking encourages students to ask not only how a water treatment plant works (technical design), but also how its implementation affects community health, resource equity, and ecological balance (systemic impact).

In educational settings, systems thinking has gained traction in fields such as sustainability science and business strategy, but its penetration into mainstream engineering education remains limited. This represents a missed opportunity. As the UN SDGs themselves represent a deeply interconnected network of goals, engineers must be trained to approach them not as isolated targets, but as a complex, interdependent system of trade-offs and synergies.

By grounding curriculum development in the principles of complexity science and systems thinking, engineering education can more effectively prepare students for the realities of contemporary professional practice—where solutions must be adaptable, ethical, and systemically informed.

3. Mapping UN SDGs into Engineering Education

The United Nations Sustainable Development Goals (UN SDGs) present an ambitious framework for addressing some of the most pressing challenges facing humanity. Comprising 17 goals and 169 targets, the SDGs span a wide range of social, economic, and environmental dimensions—from clean water and sanitation (SDG 6) to affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and responsible consumption and production (SDG 12). For engineers, these goals are not abstract ideals—they are directly actionable challenges that demand innovative, scalable, and context-sensitive solutions.

Many engineering sub-disciplines map naturally onto specific SDGs. For instance, civil and environmental engineers are key to achieving SDG 6 (Clean Water) and SDG 11 (Sustainable Cities), electrical engineers contribute critically to SDG 7 (Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure), while mechanical engineers play central roles in SDG 12 (Sustainable Production) [14], [15]. However, the interlinkages between goals demand interdisciplinary collaboration and systems-level understanding, attributes that are not always cultivated in traditional, siloed engineering programs.

Currently, in many institutions, the SDGs are introduced as stand-alone topics—often through guest lectures, final-year projects, or social innovation electives. While these efforts are commendable, they often fall short of integrating sustainability into the core fabric of engineering education. Treating the SDGs as peripheral or "add-on" content risks reinforcing the idea that sustainability is secondary to technical rigor, rather than integral to it [16].

What is needed is a paradigm shift: the SDGs must be viewed not just as ethical obligations but as design constraints and systemic drivers for engineering solutions. Embedding them within the curriculum requires rethinking learning objectives, course content, and assessment methods [17]. When approached through the lens of complexity, the SDGs become not just goals but entry points for systems analysis—challenges that students can model, simulate, optimize, and critique within real-world constraints.

By making the SDGs central to engineering formation, educators can foster a mindset that is not only technically competent but also globally conscious, ethically grounded, and systems-aware—traits essential for the 21st-century engineer.

4. Reimagining Curriculum Through Complexity & SDGs

Reorienting engineering education around complexity science and the Sustainable Development Goals (SDGs) requires more than curricular add-ons—it demands a fundamental redesign of what we teach, how we teach, and why we teach. This section outlines the principles, pedagogical shifts, and structural elements needed to build a complexity-informed, SDG-aligned engineering curriculum.

4.1 Core Principles of a Complexity-Informed Curriculum

1. Transdisciplinarity: Engineering challenges today do not respect disciplinary boundaries. Courses must bridge environmental science, public policy, ethics, economics, and design. For example, a course on energy systems should combine thermodynamics with life-cycle analysis and energy justice considerations (SDGs 7, 13, and 10).
2. Nonlinear Learning Paths: Instead of rigid progressions from "basics" to "applications," curricula should allow students to encounter complexity early through open-ended projects, simulations, and real-world case studies.
3. Systems Tools & Languages: Students should be taught systems mapping, causal loop diagrams, agent-based modeling, and scenario planning as core engineering tools—not optional techniques.
4. Iteration & Reflexivity: Problem-solving is rarely linear. Students must learn to reflect on failures, pivot solutions, and assess unintended consequences—a necessary skill in addressing complex SDG-related problems.

4.2 Pedagogical Shifts: From Teaching to Facilitation

A complexity-aligned curriculum requires a shift in the educator's role—from content deliverer to learning facilitator. Teaching must move toward project-based, inquiry-driven learning, where students grapple with ambiguous, real-world problems as shown in Table 1.

Table 1. Table Label

Traditional Pedagogy	Complexity-Informed Pedagogy
Lecture-centric	Project/problem-based
Prescriptive assignments	Open-ended challenges
Individual work	Collaborative, interdisciplinary
Technical focus only	Integration of social, ethical dimensions
Linear course progression	Modular, theme-based learning

For example, in a "Sustainable Materials" course, instead of merely teaching material properties, students might design components for affordable housing using life cycle assessments, stakeholder analysis, and circular economy principles (SDGs 9, 11, 12).

4.3 Proposed Curriculum Architecture

Here is a suggested structure that embeds SDGs and systems thinking at the program level:

Foundation Courses (Year 1–2)

- Engineering & Society: Introduction to SDGs and systems thinking.
- Mathematical Modeling of Complex Systems: Nonlinear dynamics, feedback, simulation.
- Ethics & Policy in Engineering: Social dimensions of technological solutions.

Discipline-Integrated Threads (Years 2–4)

- Each core technical course (e.g., Thermodynamics, Fluid Mechanics) includes an SDG-aligned case or module.
- Students analyze the system-level impacts of technical choices (e.g., how material choices in design affect sustainability and equity).

SDG-Aligned Electives

- Smart Cities & Resilient Infrastructure (SDGs 9, 11)
- Sustainable Energy Transitions (SDG 7)

- Climate Systems and Adaptation (SDGs 13, 6)

Capstone Experience

- Multidisciplinary teams work on real-world, SDG-linked projects in partnership with NGOs, government agencies, or industries. Students apply systems mapping, stakeholder engagement, and technical analysis to co-create sustainable solutions.

By aligning the curriculum with the principles of complexity and the ethos of the SDGs, engineering education can evolve to produce graduates who are not only proficient engineers but also adaptive systems thinkers, ethical decision-makers, and change agents for a sustainable future.

5. Institutional and Faculty Considerations

While curriculum redesign is essential, its success ultimately depends on the institutional ecosystem and the faculty mindset that support it. Reimagining engineering education through the lens of complexity and the UN SDGs is not a solitary act of course revision—it is a cultural shift that must be embraced across departments, leadership, and teaching communities.

5.1 Faculty Development & Training

Most engineering faculty are trained in traditional, discipline-specific methods, with limited exposure to interdisciplinary pedagogies, systems thinking, or SDG frameworks. Therefore, faculty upskilling is foundational. Institutions must:

- Organize faculty workshops on complexity science, systems thinking tools, and SDG mapping.
- Provide collaborative spaces for interdisciplinary curriculum design (e.g., design sprints or curriculum labs).
- Encourage co-teaching models across departments to integrate social, environmental, and policy dimensions into technical subjects.

Furthermore, faculty evaluation and incentives should recognize efforts that go beyond technical research—such as contributions to curriculum innovation, community-based projects, and transdisciplinary teaching.

5.2 Institutional Support Structures

Institutional alignment is equally critical. Leadership must signal the strategic importance of SDG-aligned, complexity-informed education through:

- Curricular autonomy: Empowering departments to design flexible, modular courses that transcend rigid syllabi.
- Interdisciplinary centres: Establishing centres for sustainability, systems engineering, or SDG research to foster cross-department collaboration.
- Partnerships with real-world stakeholders: Facilitating engagements with NGOs, local governments, and industry to offer students authentic project experiences.

Moreover, accreditation bodies (like NBA or ABET) are increasingly incorporating sustainability and ethics into their graduate attributes. Institutions must respond by aligning program outcomes with competencies such as “complex problem solving,” “environmental and social awareness,” and “lifelong learning.”

5.3 Student Engagement and Agency

Finally, students must not be seen as passive recipients of new curriculum—they should be engaged as co-creators of change. This can be done through:

- Student-led SDG hackathons or innovation challenges.
- Inclusion of students in curriculum review boards.
- Platforms like engineering-for-change clubs, or partnerships with global initiatives like Engineers Without Borders.

When students, faculty, and institutions collectively embrace systems thinking and the SDGs as central to engineering education, the impact is transformative—not only for academic programs, but for society at large.

6. Conclusion & Future Directions

The challenges of the 21st century—climate change, resource scarcity, urban resilience, and equitable development—require engineers who can do far more than solve isolated technical problems. They must be prepared to understand and navigate complex, interconnected systems, weigh ethical trade-offs, and co-create sustainable solutions with diverse stakeholders. This demands a paradigm shift in engineering education—one that embraces the principles of complexity science and integrates the UN Sustainable Development Goals (SDGs) not as peripheral topics, but as foundational elements of learning and professional identity.

Through the lens of complexity, engineering problems are no longer limited to design specifications or performance metrics. They become open-ended, evolving challenges embedded in social, economic, and ecological contexts. A curriculum that reflects this reality must empower students to think in systems, operate across disciplines, and act with foresight and responsibility. Embedding the SDGs into the fabric of engineering education is not only a curricular innovation—it is a moral imperative.

This article has proposed a pathway to realize this transformation. It includes integrating systems thinking into foundational and advanced courses, aligning capstone projects with real-world SDG challenges, reshaping faculty development, and enabling institutional structures that reward interdisciplinarity and social impact. Together, these actions form a cohesive strategy to reimagine engineering education for a sustainable and complex world.

Looking ahead, there are several directions for future development:

- Assessment frameworks must evolve to measure not just technical competence, but also systems reasoning, ethical awareness, and collaborative problem-solving.
- Longitudinal studies are needed to track how complexity-informed, SDG-aligned education impacts graduates' professional trajectories and real-world decision-making.
- Policy-level engagement with national accreditation bodies and education ministries can help scale and formalize such curriculum innovations across institutions.

Ultimately, the future of engineering lies not just in smarter algorithms or more efficient designs, but in smarter, more empathetic, and more systemically aware engineers. Reimagining education through complexity and sustainability is not a radical departure from engineering's mission—it is a return to its truest form: building a better world.

References

[1] S. Mazzetto, "Interdisciplinary Perspectives on Agent-Based Modeling in the Architecture, Engineering, and Construction Industry: A Comprehensive Review," Buildings, vol. 14, no. 11, Art. no. 11, Nov. 2024, doi: 10.3390/buildings14113480.

[2] V. S. Vassiliadis et al., "Reloading Process Systems Engineering within Chemical Engineering," Chem. Eng. Res. Des., vol. 209, pp. 380–398, Sep. 2024, doi: 10.1016/j.cherd.2024.07.066.

[3] L. Volodzkiene and D. Streimikiene, "Energy Inequality Indicators: A Comprehensive Review for Exploring Ways to Reduce Inequality," Energies, vol. 16, no. 16, Art. no. 16, Jan. 2023, doi: 10.3390/en16166075.

[4] B. B. Lin et al., "Integrating solutions to adapt cities for climate change," Lancet Planet. Health, vol. 5, no. 7, pp. e479–e486, Jul. 2021, doi: 10.1016/S2542-5196(21)00135-2.

[5] A. Bustamante-Mora, M. Diéguez-Rebolledo, Y. Hormazábal, L. Millar, and R. Cadena, "Challenges and Opportunities for Sustainable Engineering: Products, Services, Technologies, and Social Inclusivity with a Gender Approach," Sustainability, vol. 16, no. 5, Art. no. 5, Jan. 2024, doi: 10.3390/su16051888.

[6] H. Hassani, X. Huang, S. MacFeely, and M. R. Entezarian, "Big Data and the United Nations Sustainable Development Goals (UN SDGs) at a Glance," Big Data Cogn. Comput., vol. 5, no. 3, Art. no. 3, Sep. 2021, doi: 10.3390/bdcc5030028.

[7] F. Sánchez-Carracedo et al., “Tools for Embedding and Assessing Sustainable Development Goals in Engineering Education,” Sustainability, vol. 13, no. 21, Art. no. 21, Jan. 2021, doi: 10.3390/su132112154.

[8] Y. Karaca, “Chapter 2 - Theory of complexity, origin and complex systems,” in Multi-Chaos, Fractal and Multi-Fractional Artificial Intelligence of Different Complex Systems, Y. Karaca, D. Baleanu, Y.-D. Zhang, O. Gervasi, and M. Moonis, Eds., Academic Press, 2022, pp. 9–20. doi: 10.1016/B978-0-323-90032-4.00003-1.

[9] H. Qudrat-Ullah, “Systems Thinking and Sustainability Education in Practice,” in Systems Thinking for Sustainability Education in Business Schools, H. Qudrat-Ullah, Ed., Cham: Springer Nature Switzerland, 2024, pp. 31–54. doi: 10.1007/978-3-031-61077-6_3.

[10] H. Jalonen, “A complexity theory perspective on politico-administrative systems: Insights from a systematic literature review,” Int. Public Manag. J., vol. 28, no. 1, pp. 1–21, Jan. 2025, doi: 10.1080/10967494.2024.2333382.

[11] D. Jerab, “An Overview of Complexity Theory and Characteristics of Complex Adaptive Systems,” Jan. 12, 2025, Social Science Research Network, Rochester, NY: 5094533. doi: 10.2139/ssrn.5094533.

[12] H. Nguyen and R. Santagata, “Impact of computer modeling on learning and teaching systems thinking,” J. Res. Sci. Teach., vol. 58, no. 5, pp. 661–688, 2021, doi: 10.1002/tea.21674.

[13] D. Cabrera and L. Cabrera, “What Is Systems Thinking?,” in Learning, Design, and Technology, Springer, Cham, 2023, pp. 1495–1522. doi: 10.1007/978-3-319-17461-7_100.

[14] V. L. Trinh and C. K. Chung, “Renewable energy for SDG-7 and sustainable electrical production, integration, industrial application, and globalization: Review,” Clean. Eng. Technol., vol. 15, p. 100657, Aug. 2023, doi: 10.1016/j.clet.2023.100657.

[15] L. Addagada, S. T. Ramesh, D. N. Ratha, R. Gandhimathi, and P. R. Rout, “The Role of Civil Engineering in Achieving UN Sustainable Development Goals,” in Advances in Sustainable Materials and Resilient Infrastructure, K. R. Reddy, R. K. Pancharathi, N. G. Reddy, and S. R. Arukala, Eds., Singapore: Springer, 2022, pp. 373–389. doi: 10.1007/978-981-16-9744-9_25.

[16] T. Chau, “Intersection of Profit and Purpose: Marketing Strategies in the Impact Investing Landscape for Startups.” Accessed: Jun. 10, 2025. [Online]. Available: http://www.theseus.fi/handle/10024/890258.

[17] K. Daubney, “‘Teaching employability is not my job!’: redefining embedded employability from within the higher education curriculum,” High. Educ. Ski. Work-Based Learn., vol. 12, no. 1, pp. 92–106, Aug. 2021, doi: 10.1108/HESWBL-07-2020-0165.