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Sustainable Morphing Matter: Design and Engineering Practices

*Dinesh K. Patel, Ke Zhong, Haiqing Xu, Mohammad F. Islam, and Lining Yao**

Morphing matter that change shapes and properties in response to external stimuli have gained significant interests in material science, robotics, biomedical engineering, wearables, architecture, and design. Along with functional advances, there is growing pressure and interest in considering the environmental impact of morphing matter during its life cycle. The unique manufacturing and usage of morphing matter means that existing sustainable design frameworks and principles for general physical products may not apply directly. For example, manufacturing morphing matter often requires designing and predicting materials' behaviors over time, and using devices fabricated with morphing matter often involves harnessing renewable energy and self-reconfiguration, which pose unique sustainability opportunities and challenges. This study reflects and summarizes the field's practice in sustainable manufacturing, transport, use, and end-of-life handling of morphing matter. The term "sustainable morphing matter" (SMM) is coined, suggesting that sustainability-conscious factors can become an integral component of morphing matter. In addition, ways to apply sustainability-conscious factors to augment the existing design pipeline of morphing matter are presented, and more quantitative and algorithmic-level developments are needed to apply these factors rigorously to the design process.

1. Sustainable Morphing Matter (SMM)

Morphing matter refers to a class of active materials that can be controlled to change shape, properties, or functionalities due to external stimuli. These stimuli can include temperature, pH, moisture, pressure, electric, and magnetic fields. Engineering and studying morphing matter involves material science, physics, chemistry, engineering, design, and computer science. Ongoing research and innovation focus on developing new morphing matter with advanced properties and functionalities, which has the potential to revolutionize many aspects of technology. Over the past decades, the concept of morphing matter has fascinated scientists and engineers, leading to the development of a wide variety of smart materials in various fields, such as biomedical engineering,[1–3] robotics,[4–8] energy,[9–11] and aerospace.[12,13]

Along with advancing the technical frontier and utilities of morphing matter, researchers have placed increasing attention on sustainable designs. Holistic design guidelines[14,15] are emerging to help the field in seeking a unified workflow for considering sustainable design practices. **Figure 1** shows examples of both engineered and natural morphing matter used as-is or in fabricated devices, actuators, and robots, along with their respective approaches to integrate sustainable design considerations. Examples of engineered morphing matter include biodegradable hygromorphic matter used to design self-burying devices that use renewable energy to execute tasks,[16] edible morphing matter manufactured with energy-saving stamping approaches and transported with space-saving flat-pack methods,[17] hydraulic morphing matter to make grippers designed with end-of-life considerations,[18] self-healing morphing matter-enabled robots that effectively extend their life under harsh conditions,[19–21] and morphing textiles relying on mechanical computation that is electronic-free and battery-free.[22–24] Beyond engineered systems with morphing matter, there are numerous natural morphing matter-embedded systems that embrace sustainable design principles. These include wild oat awn that walks and snaps to disperse seeds by harvesting ambient moisture fluctuations,[25] hygromorphic plant tissues and microorganisms including *Erodium* seed awn,[26] wood veneer,[27] pine cone scales,[28] chiral seedpod,[29] and *Bacillus*

D. K. Patel, K. Zhong, H. Xu, L. Yao
Morphing Matter Lab
Human-Computer Interaction Institute
School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213, USA
E-mail: liningy@andrew.cmu.edu
K. Zhong, M. F. Islam
Department of Materials Science and Engineering
Carnegie Mellon University
Pittsburgh, PA 15213, USA
H. Xu
Academe Arts and Design
Tsinghua University
Haidian, Beijing 100084, China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/admt.202300678

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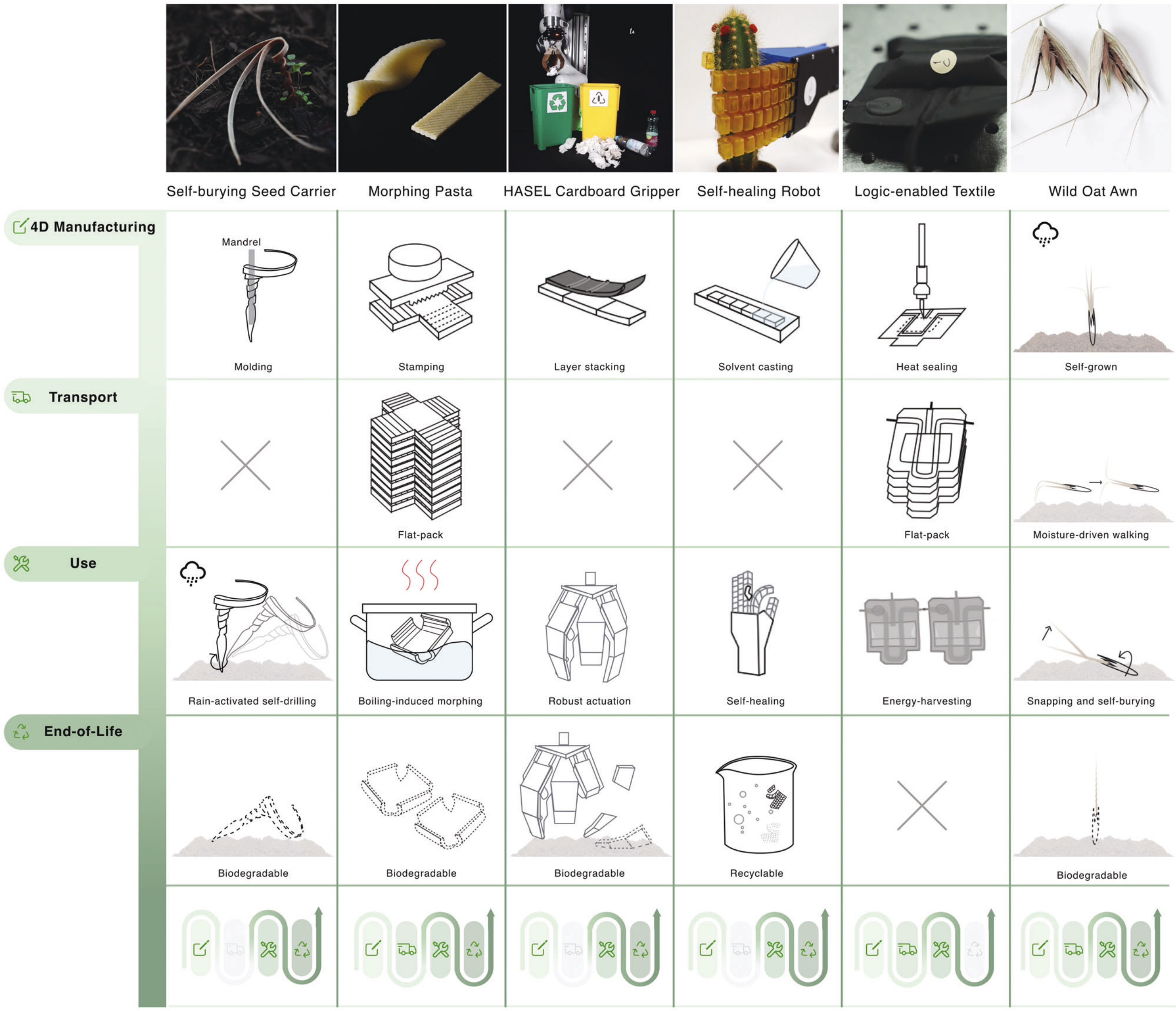

Figure 1. Representative examples of sustainable morphing matter (SMM), whether used in its natural form or incorporated into devices, actuators, and robots, demonstrating different approaches to integrate sustainable design considerations into the engineering and use of morphing matter. The examples include self-burying seed carrier. Reproduced with permission.[16] Copyright 2023, Springer Nature. Morphing pasta. Reproduced under the term of CC-BY license.[17] Copyright 2021, The Authors, published by American Association for the Advancement of Science. HASEL cardboard gripper. Reproduced under the term of CC-BY license.[18] Copyright 2023, The Authors, published by American Association for the Advancement of Science. Self healing robot.[19,31] Reproduced under the term of CC-BY licence.[19] Copyright 2017, The Authors, published by American Association for the Advancement of Science. Reproduced under the term of CC-BY license.[31] Copyright 2019, The Authors, University of Cambridge. Logic-enabled textile.[22,32] Reproduced under the term of CC-BY license.[22] Copyright 2022, National Academy of Sciences. Reproduced with permission.[32] Copyright 2022, Rice University. Wild oats awns. Reproduced with permission.[25] Copyright 2021, Elsevier.

Subtilis bacteria.[30] These natural morphing matter-based systems are grown, transported, and used in a sustainable manner, harvesting ambient energy for actuation and eventually degrading into natural environments.

Recently, scientists and engineers are called upon to minimize impacts on the environment by considering five strategies: lifetime extension, dematerialization, manufacturing efficiency, substitution, and recovery.[33] Inspired by this call, we propose a conceptual framework for sustainable morphing matter (SMM). Here, we use SMM to refer to morphing materials that are designed with the consideration of sustainability-conscious factors during four phases including four-dimensional (4D) manufacturing, transport, use, and end-of-life. During each phase, energy and material consumption can be considered while generating, refining and evaluating morphing matter design and optimization strategies.

2. Sustainability-Conscious Factors

Sustainability is integral to the lifecycle of morphing matter, which consists of four phases: 4D manufacturing, transport, use, and end-of-life (**Figure 2**). Within each phase, there are key

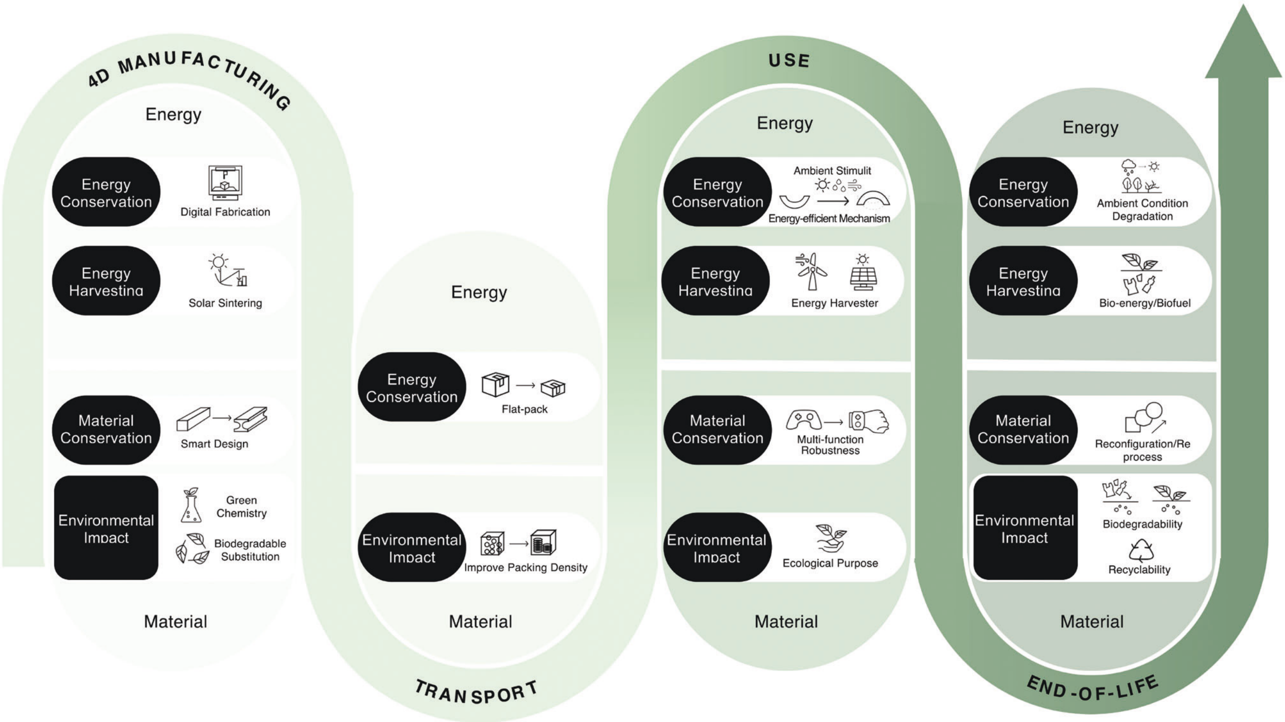

Figure 2. Sustainability-conscious design factor. 4D manufacturing, transport, use and end-of-life are the four phases of the life cycle of morphing matter-based systems.

factors critical to achieving sustainability, and specific technologies and solutions have been developed to address these factors from either an energy or material perspective. By summarizing these sustainability-conscious factors and associated technologies or solutions, we aim to provide a comprehensive understanding of sustainability in the context of morphing matter.

2.1. 4D Manufacturing

The "4D" term refers to the fourth dimension, which is time. 4D manufacturing is inspired by the notion of 4D printing,[34] yet it goes beyond it. Here, 4D manufacturing refers to a set of manufacturing techniques employed to fabricate morphing matter that can respond to external stimuli and change shapes and other physical properties after the manufacturing is completed (**Figure 3**). These materials do not necessarily change shape during the manufacturing phase, similar to how materials may not undergo shape transformations during the printing process in the context of 4D printing.[34] 4D manufacturing can be achieved by various existing manufacturing technologies, such as printing, stamping, casting, heat sealing, layer stacking or lamination, molding, and textile manufacturing techniques.

Printing technologies can broadly include various known two-dimensional (2D), three-dimensional (3D), and 4D printing techniques.[35–38] Under 2D printing, we have seen morphing matter via inkjet printing with pre-stressed polymer sheets,[39] and screen printing of hygroscopic bioink on polyimide films,[40] etc. As one of the most popular techniques for manufacturing morphing matter, 3D and 4D printing techniques have been broadly adopted for heat-responsive shape memory materials,[41–43] light-responsive polymers,[44–47] biotic morphing materials,[48,49] among other examples.

Beyond printing, other manufacturing technologies can also be used for morphing matter. For instance, layer stacking was used for both wood and thermoplastic-based morphing structures.[50,51] In addition, surface features that affect morphing behaviors can be created by processes such as imprinting, stamping, casting, etching, or milling. For example, morphing pasta was manufactured using stamping, and morphing polydimethylsiloxane (PDMS) strips with groves were fabricated using casting.[17] In both cases, specific morphing behaviors were observed due to differential swelling. Moreover, pneumatically driven inflatables were fabricated by heat sealing of flat structures,[52] and textile manufacturing techniques such as 3D knitting were used to create morphing matter with embedded actuating mechanisms.[53,54]

The 4D manufacturing approach and efficiency are crucial factors to consider. In terms of energy consumption, factors such as the source of energy, the choice of manufacturing approaches, and the design of fabrication files play critical roles in determining the energy consumption of SMM. (i) Regarding the sources and types of energy, different approaches cost different amounts of energy. For instance, room-temperature manufacturing processes can require less energy than high-temperature processing. Furthermore, it has been attractive for researchers to develop energy harvesting mechanisms to either power or assist the manufacturing processes. For example, solar sintering makes it possible to harness energy from the sun for 3D printing,[55] promoting sustainable manufacturing practices. (ii) When

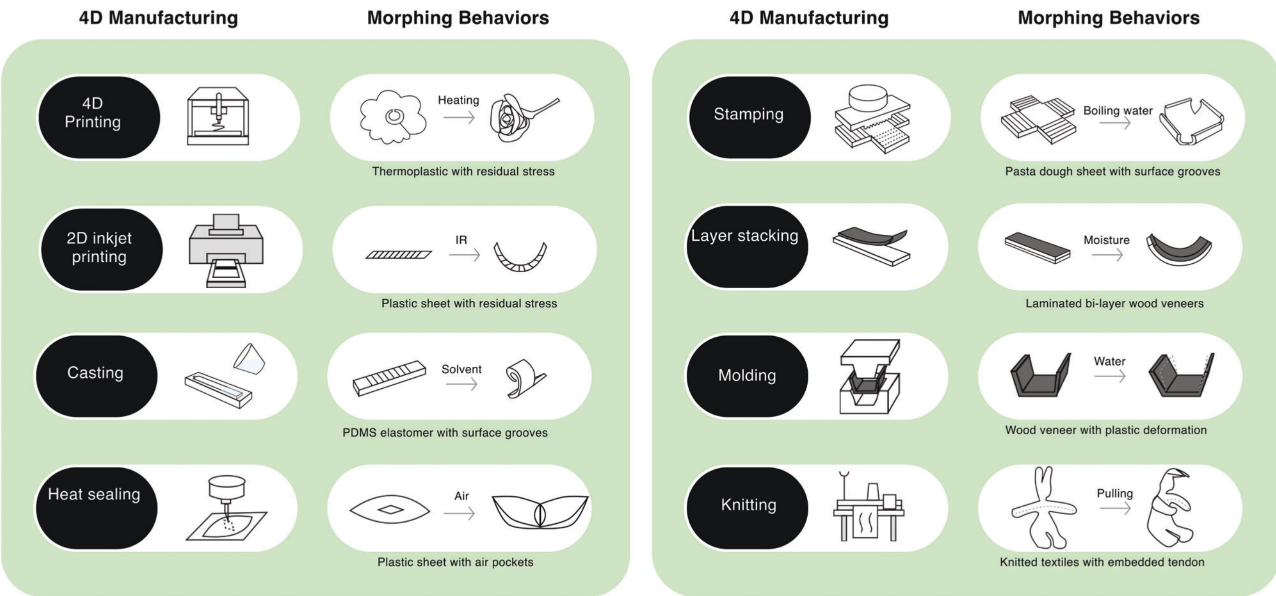

Figure 3. 4D manufacturing approaches utilized for manufacturing morphing matter, handling a variety of materials. 4D manufacturing refers to various existing processes that include additive manufacturing (AM) techniques such as 2D, 3D, and 4D printing, as well as subtractive manufacturing techniques such as milling, etching, and other common manufacturing approaches including stamping, casting, layer stacking, molding, and heat sealing.

multiple approaches are technically feasible, energy consumption can be an additional factor when making decisions for the choice of 4D manufacturing approaches. For the case of printing self-foldable structures from 2D to 3D, the manufacturing time for the initial 2D construct will likely be shorter than the time required for directly fabricating the target 3D shape.[56] In addition, morphing structures achieved through simple stamping[17] might consume less energy during the manufacturing phase than processes such as extrusion-based 4D printing. (iii) Techniques such as digital fabrication and AI-based computational design and optimization can be leveraged to improve the efficiency of 4D manufacturing.[57–59] For example, 3D printing enables the precise and efficient production of complex geometries, and computational design can optimize the design of morphing matter, resulting in an effective printing toolpath with optimized energy consumption.

Sustainability can be promoted from a material perspective by minimizing material consumption and negative impact on the environment. Materials can be saved by improving the yield rate, saving and reusing supporting materials, and optimizing the manufacturing process. For example, topological optimization can be leveraged to design structures smartly to reduce material consumption while maintaining the required mechanical properties,[60] and some 4D printing approaches can minimize the use of support materials.[61,62] On the other hand, we should seek more environmental-friendly materials or fabrication methods. In this context, biodegradable materials can serve as sustainable alternatives, particularly for functional systems intended for deployment in natural settings, as they are challenging to recycle and must be environmentally friendly. For example, plant- and microorganism-based biomaterials that are biodegradable and responsive have been designed for functional devices,[63] robots,[64,65] and actuators.[66–68] Another critical factor is waste management during the manufacturing process.[69] While reducing waste is important, the toxicity of waste should also be minimized through strategies such as green chemistry.

2.2. Transport

While sustainability considerations often focus on the manufacturing and use of morphing matter systems, transport is a crucial component that bridges these stages but is frequently overlooked. One design concept is related to flat-pack during transportation and on-site self-deployment via morphing. Since many 4D-manufactured morphing structures are planar, they can be packed in a space-saving manner. Once on-site or during utilization, they can self-morph into target shapes. Morphing food design is one such example. The usage of plastic in food packaging is a significant contributor to landfills in the United States, which emphasizes the need to adopt sustainable food packaging methods. One proposed solution is to create morphing food, which can be flattened for more efficient packaging during storage and transportation.[17,70] Similar flat-pack and on-site deployment ideas have been explored in designing furniture with morphing wood and plastics,[71,72] multi-stable origami structures for deployable tent,[73,74] and self-morphing clay and ceramic structures with potential future uses in natural restoration underwater.[75,76]

2.3. Use

Energy-efficient use of morphing matter can be achieved through the utilization of ambient stimuli or energy-efficient mechanisms. (i) Many morphing materials are inherently responsive to ambient stimuli and require no external power supply. These stimuli include sunlight,[77–79] rain,[16] moisture in the air,[80] geothermal energy,[81] wind,[9,82] and biofuels.[83] Design opportunities exist in amplifying the inherent stimuli-responsiveness of these morphing materials with compositional or structural mechanisms to push the boundary in terms of scale, speed, programmability, and computational potential of these SMM. (ii) Beyond stimuli-responsiveness, some SMM are engineered to harvest and store energy through different energy transduction paradigms, i.e., embodied energy.[84] For example, embedded thermoelectric components in liquid crystal elastomer-based morphing matter could help with improving actuation speed and harvesting ambient thermal energy.[79,85] (iii) The use of energy-efficient morphing mechanisms can also reduce energy consumption. For instance, bistable or multi-stable morphing matter-based systems can remain stable in different states without requiring a constant supply of external energy.[86–88] Here, energy is only necessary to overcome the energy barrier during the transition process. Besides energy conservation, these multi-stable mechanisms often help achieve faster motions such as jumping, snapping, and explosive dispersal by leveraging mechanical instability for power amplification in both engineered[89,90] and natural contexts.[91,92]

In terms of materials, sustainability during use is often linked to the reconfigurability of shape and function. By reconfiguration, the properties of SMM-based systems can be altered to achieve new functionalities that extend their lifespan, use cases, and adaptability. (i) Shape memory SMM-based devices can serve multiple purposes with reconfigurable shapes or structures. For instance, the shape memory effect of epoxy has been utilized to transform an input device into three states, adapting to different application scenarios.[93] (ii) Self-healing and self-repairing features of morphing matter help elongate the lifetime of functional systems and allow for reconfiguration. For example, self-healing materials can be used to fix damages on wearable devices and allow for new shape and function reconfigurations of a handheld controller by breaking and rejoining the dynamic bonds.[21,94,95] (iii) Systems designed with morphing matter that evolve over time, through techniques such as self-organizing,[96] phase shifting,[97] self-growth,[98,99] and controlled degradation, destruction, and evolution[100,101] may also achieve multi-functionalities. Additionally, morphing matter can promote sustainability by serving ecological purposes. For example, some SMM are designed for natural restoration or environmental monitoring purposes.[102–105]

2.4. End-of-Life

The end-of-life phase of morphing matter is a critical aspect of its overall sustainability. We categorize the common end-of-life processing of SMM into three types: reprocessing, recycling, and degradation. Reprocessing involves breaking down the material into its basic components through methods such as dissolution or grinding. The resulting material can then be repurposed for different applications, reducing the need for new raw materials. Poly(lactic acid) (PLA) filament used for 3D printing is often reprocessed in this manner to produce new filaments.[106] Chemically recycling involves converting the polymer into monomers or oligomers through chemical reactions. This approach can be used to produce new materials or regenerate the original material. For example, chemically recyclable thermosetting polymers for digital light processing 3D printing have been proposed previously.[107] For degradation, various naturally derived or engineered morphing matter have been introduced for their biodegradability, such as those described in refs. [14, 108–111].

To further enhance the sustainability of morphing matter, the conservation or even harvesting of energy during this stage can be explored. One approach is to design morphing matter to degrade under ambient conditions, which can save energy and reduce the need for additional processing.[112] Additionally, SMM made of organics and biomass can be converted into useful forms of energy such as heat, electricity, and fuel during their natural degradation.[113] This approach can potentially provide an additional source of energy while also reducing waste and greenhouse gas emissions.

3. Design Pipeline for SMM

We suggest a design pipeline that integrates sustainability-conscious design criteria into the design and optimization process of morphing matter. A general design pipeline of systems related to morphing matter involves both physical experiments and computational designs. It often starts by establishing design goals and deriving design solutions including both morphing mechanisms and tailored manufacturing approaches, followed by formulating optimization goals and constraints, as well as identifying optimization approaches and then evaluation strategies.

When identifying design solutions, sustainability-conscious factors discussed earlier (**Figure 4**) can be applied as additional considerations, which may result in changing the initial design solutions and even design goals. For example, if the design goal is to develop an amphibian robot for environmental monitoring purposes, the initial design solutions can be chosen from many existing soft morphing matter technologies. Once sustainability-conscious factors are applied, one may choose to use casting over printing (for manufacturing), make it flat-pack or have it self-assemble on site (for transport), adapt or invent a self-powered and energy-efficient bi-stable actuating mechanism (for use), and choose biodegradable materials to design the robot with (for end-of-life). Based on the updated design solutions, optimization goals, and strategies have to be updated as well. To integrate sustainability-conscious factors into the optimization process, it is critical to come up with mathematical or conceptual models that capture the relationship between the sustainability-conscious design objectives (optimization goals) and the constraints. These models will allow one to identify ideal solutions to achieve the objectives while satisfying the constraints via either experimental or numerical optimization approaches. For example, a tailored mathematical model of energy consumption can be integrated into the multi-objective optimization process of a fluidic actuator with an energy-saving trajectory.[114] We believe more research is needed in developing tailored and comprehensive numerical models that describe sustainability-conscious objectives related to morphing matter.

4. Challenges and Perspectives

The study of SMM is a relatively new area of research. Researchers and scientists are very excited to develop morphing

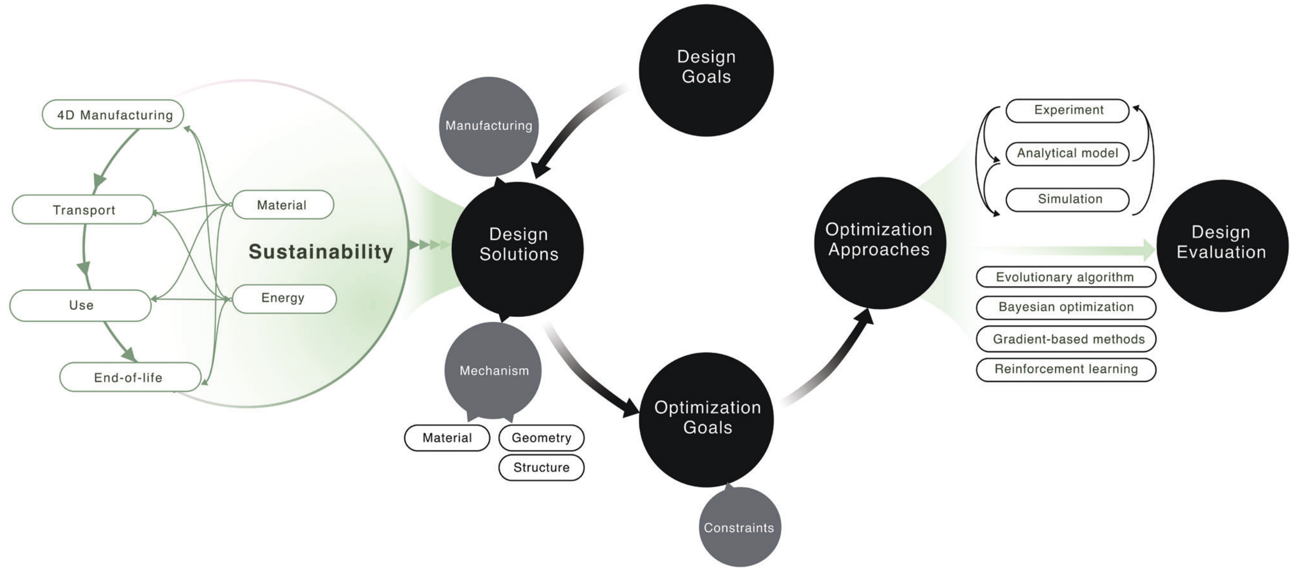

Figure 4. Design pipeline for SMM. Sustainability-conscious factors can be applied when design solutions are generated, which are subsequently formulated into mathematical or conceptual models for design optimization.

materials and technologies that revolutionize various industries including robotics, medicine, dentistry, agriculture, consumer products, and space-related applications. We have highlighted the promise of SMM to reduce the severe impact on the environment by considering the materials and energy consumption, as well as by making the process of manufacturing and usage both human and environmentally friendly. However, SMM also face challenges that need to be further addressed for their widespread adoption.

There is a need for the development of new morphing materials that are both sustainable and functionally robust. During the material development, it should be produced using renewable resources and its entire lifecycle and disposal should be considered along with desired functions. Design goals should be set during manufacturing in a way that not only consumes less energy and material but also produces less or no waste. Another opportunity lies in the engineering of better-performed natural materials, as naturally-derived morphing materials are often slow in actuation and with inferior mechanical properties. For engineered options, multi-stimuli responsive and self-computing morphing matter are highly desired. Another challenge in the development of SMM is investment in research and development. At this stage, the cost of production is high and cannot be easily adopted for certain applications. The current state of the art for SMM is mostly at a laboratory scale, and scaling up to meet the growing demand is a challenge. For an intended application, the performance of the materials should meet a particular standard. The materials should be reliable, durable, and able to withstand various environments. The manufacturers should be able to trust in newer technology of sustainable morphing matter.

We envision that SMM has an opportunity to revolutionize various industries, but need further development, adoption, and trust as mentioned above. For example, a multimodal robot that can adapt to various tasks and terrains can be developed by using SMM. This will save manufacturing costs and time as one robot can perform multiple tasks. In aerospace, an adaptive wing for aircraft for changing flight conditions could be developed using SMM. SMM could also play a crucial role in space missions and explorations. For the Mars missions and settlements, SMM may be employed at larger scales for soil sampling and environmental monitoring by utilizing temperature fluctuations for mechanical movements. It can also revolutionize the field of medicine, i.e., drug delivery, tissue engineering, and healing of wounds. On-demand SMM manufactured using 4D manufacturing can transform into complex shapes or structures like self-assembled structures, for applications in architecture and construction industries. SMM can also play an important role in the textile industry as one can imagine a dress that can fit all sizes. Researchers, scientists, engineers, and manufacturers should collaborate and work together as a joint force to make our planet and even the universe greener and more sustainable. Research and development in this area should also focus on scalability in manufacturing and explore new applications and markets for these materials.

5. Conclusion

With growing population demands and climate changes, sustainable solutions are needed on a priority basis to reduce environmental impact and use resources efficiently. Here, sustainable morphing matter is proposed to highlight the importance of considering the sustainable life cycle when designing morphing matter-based systems, encompassing manufacturing, transportation, usage, and end-of-life stages. It has the potential to make the design and manufacturing of morphing structures, actuators, and robots more sustainable. Sustainability should be prioritized by researchers, manufacturers, and policymakers in decision-making processes. It is essential to invest in sustainable morphing matter technologies and promote sustainable practices throughout each phase of production. This commitment will contribute to creating a greener future for both people and our planet, including Earth and outer space.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

4D manufacturing, 4D printing, biodegradability, life cycles, morphing matters, recycling, sustainability

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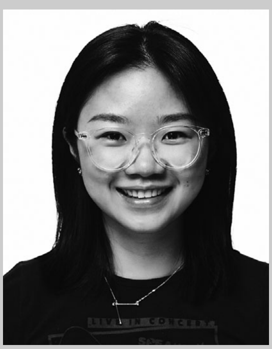
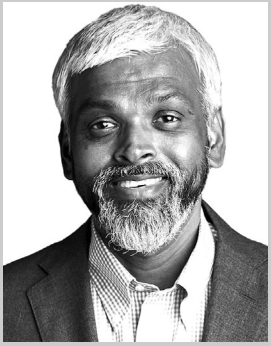
Dinesh K. Patel received his B.S. and M.S. degrees in chemistry from the University of Mumbai, India, and the Ph.D. degree in chemistry from the Bhabha Atomic Research Centre, University of Mumbai, in 2014. He is currently a post-doctoral researcher with Carnegie Mellon University. Prior joining to Carnegie Mellon University, he worked as post-doctoral fellow at The Hebrew University of Jerusalem, Israel, from 2014 to 2018. He has coauthored over 35 refereed journal and conference publications. Some of his work is featured as front cover in reputed Journals like Nature, Advanced Materials Technologies and ACS Sustainable Chemistry & Engineering. His research interests include functional 3D printing at micron and mm-scale, soft robotics, actuators, morphing materials, printed electronics, and mechanoluminescent devices.



Ke Zhong received her B.S. degree in materials science and Engineering from Southern University of Science and Technology in China in 2020. She is currently a Ph.D. candidate at Carnegie Mellon University advised by Prof. Mohammad F. Islam and Prof. Lining Yao. She works in the interdisciplinary area of Materials Science and Engineering and Human-Computer Interaction. Her research interests include morphing materials, active soft materials, self-healing polymers, and soft robotics.

Haiqing Xu is a researcher, interaction designer, and artist, collaborating with Morphing Matter Lab advised by Prof. Lining Yao. She is a Master's student at the Future Lab and Media and Interaction Lab at Tsinghua University, advised by Haipeng Mi. She works in the area of Human-Computer Interaction (HCI) within the field of creativity support tools and computational fabrication. She received her B.S. in product design at the Beijing Institute of Fashion Technology and as an exchange student in Fashion Design at the Polytechnic University of Milan.



Mohammad F. Islam is a Professor in the Department of Materials Science and Engineering at Carnegie Mellon University and co-leads the university's Softbotics initiative. His group employs both soft- and nanomaterials to engineer multifunctional materials with tailored optical, electrical, thermal, and mechanical properties. The group also explores use of these unique materials in diverse applications such as fuel cells, supercapacitors, drug delivery vessels, robotics, etc. Islam has received the Hoechst Celanese Excellence in Polymer Science Award, National Science Foundation CAREER award, the Sloan Research Fellowship, the Kavli Fellowship, and Carnegie Mellon College of Engineering George Tallman Ladd Research Award.

Lining Yao is the Cooper-Siegel assistant professor at the Human-Computer Interaction Institute of the School of Computer Science at Carnegie Mellon University (CMU), where she directs the Morphing Matter Lab (morphingmatter.cs.cmu.edu). She serves as a core team member of the Softbotics initiative and on the University Advisory Board of the Future Manufacturing Institute. Her research explores the positive impact of active and morphing materials on sustainable design across different scales and contexts. Her work focuses on discovering and studying morphing material mechanisms, as well as algorithms for computational design and fabrication pipelines.