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Exploring the intersection of biology and design for product innovations

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ABSTRACT

Design, development, productization, and applications of advanced product concepts are pressing for higher multifunctionality, resilience, and maximization of available resources equitably to meet the growing and continuing demands of global customers. These demands have further accelerated during the recent COVID-19 pandemic and are continuing to be a challenge. Engineering designs are one of the most effective ways to endow products with functions, resilience, and sustainability. Biology, through millions of years of evolution, has met these acute requirements under severe resource and environmental constraints. As the manufacturing of products is reaching the fundamental limits of raw materials, labor, and resource constraints in terms of availability, accessibility, and affordability, new approaches are a call to action to meet these challenges. Understanding the designs in biology is an attractive, novel, and desired frontier for learning and implementation to meet this call to action. This is the focus of the paper discussed through examples for convergence of fundamental engineering design concepts and the lessons learned and applied from biology.

1. Introduction

Biology is at the intersection of living and non-living worlds. The prime driver for biology is to survive and thrive by using the opportunity space at this interface. This interface poses acute boundary conditions for space, time, physical parameters like temperature/climatic conditions, predators, and much more. With these boundary conditions, the objective of survival and growth is an ‘almost’ insurmountable challenge for over eight million species in the water, on the land, and in the air over thousands of years. It is noteworthy that biology achieves the co-existence of these many species by equipping all with strategies for survival across all length scales (from nano-scale viruses to macro-scale animals), and across varying habitats, while maximizing the available resources through the utilization of frugality or frugal engineering principles [145].

Through the lens of manufacturing science and engineering, the above situation is rather no different than living human and non-living machines interfaces. Humans and industries are finding better ways to survive and thrive. From Industry 1.0 to Industry 4.0 (I 4.0), the physical and digital machines are growing in number per capita, and human-machine interfaces are growing rapidly and becoming more complex by posing several boundary conditions due to their mass, energy footprint, speed, and big data, and management, security and many more. With these parallels between the biology-non-living world and human-machine interfaces, it is innovative but at the same time essential that the biological ecosystem can be an effective medium to learn from for functional, frugal, and resilient approaches to establish a diverse and harmonic ecosystem nature and machines.

Further to the above complexity, since the onset of this century, consumer demands, climate issues, and pandemics have shaped and will shape production engineering and science. Global trends such as population growth, resource depletion, urbanization, and others further pose stringent boundary conditions to meet these challenges. Demand for advanced products and manufacturing technologies such as electric vehicles, sensors for autonomous vehicles, thermal management of battery stacks, light-weighting of automotive and aerospace components, and product deliveries at point-of-care in synchronous and asynchronous modes, and more are shaping new products and business models. The term advanced product refers to the development of novel products and methodologies advancing the current state-of-the-art necessary to address the above challenges while being economically, socially, and environmentally conscious. These challenges are opportunities for design science and engineering to advance. In a broad scope, design is a manifestation of creativity along with purposefulness represented through the medium of a genre of interest. Design is a tech-socioeconomic discipline, rather than a science, technology, engineering, and mathematics (STEM) endeavor.

Finally, it is noteworthy that when this paper was written, the production community and the world were still in the middle of the COVID-19 pandemic for more than two years. The pandemic taught us key lessons that are critical from the perspective of this paper. The

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Table 1
Observations from the COVID-19 pandemic and key manufacturing lessons for implementation. Table reproduced with permission from [15].

Observations	Lesson(s) learned
The physical technology most crucial for curbing the COVID-19 spread is a mask [144].	The effectiveness of a solution is not tied to design complexity but to the function, it provides with simplicity.
Heightened demand for personal protective equipment (PPE) along with masks resulted in them being manufactured by several industries that do not traditionally cater to them [162, 172, 205].	The adaptability of existing infrastructure is important. Rapid re-tooling and turnaround are needed to aid reconfigurability by repurposing existing equipment and knowledge.
Low-cost solutions were encouraged and implemented through innovations developed within the local communities [72, 91, 143, 166, 177, 198].	Cost-barrier can be overcome by a frugal engineering approach involving off-the-shelf components using minimal resources.
Industries that rely on large and complex manufacturing processes and systems were severely impacted (e.g., meat manufacturing plants) [241].	A small manufacturing footprint close to the point-of-need is necessary.

observation and the lessons are captured in Table 1. It should be noted that the lessons denoted in Table 1 summarize observations at the start of the pandemic in early 2020. As the pandemic spread all over the world, it catastrophically affected our way of life thus challenging the resilience of society. Before the scientific and technological advancements in medicine and vaccinations, this period relied on the use of masks and rapid measures to effectively minimize the damage caused by the sudden disruption caused by the deadly virus.

The above lessons (underlined in the right column, Table 1) are successfully applied by biology using a rich suite of design architectures and are a great learning platform for production scientists and engineers for major advancements. It is also noteworthy that biology is equitable (offering survival strategies to all species) and designs are effective in providing that equity, which is essential for advanced socially conscious products in the human-machine-society ecosystem. Fig. 1 shows some of the interconnecting and interdependent design strategies applied in biology to deliver a collective balance for multifunctionality, resilience, and frugality while balancing the trade-offs between efficacy, effectiveness, and efficiency. This paper presents an analysis of these strategies observed in biology, through the lens of design theory and methodology, from biology-to-bio-inspired science and engineering-to-product innovations for advancements.

The principles of frugal engineering, circular life cycle, and resiliency in biology offer a great example platform to study biology-based approaches toward sustainability in manufacturing. This topic is a part of ongoing efforts within the CIRP community as evidenced through key publications over the recent years [34,36,92,93,102,116,157,170,219], and is beyond the scope of discussion for this manuscript.

The thesis of applying biology in manufacturing, as a part of the biologicalisation strategy, includes bio-inspired, biomimetic, bio-intelligent, and bio-integrated approaches [35]. These modes of implementing biology allow a suite of avenues to advance products within the human-machine ecosystem, alike the biological ecosystem. This publication focuses primarily on bio-inspired and biomimetic avenues for product designs and innovations. The authors present their findings through sections addressing design theory, models, design structures and purpose, and applications at the intersection of biology and synthetic production science and engineering subjects.

2. Design theory and methodology for bio-inspiration

This section is driven by the inquiry for discovery, ‘if and what are parallels in biological and state-of-the-art synthetic design framework currently applied in production engineering, and how we one can use those discoveries to advance the state-of-the-art in design theory and methodology’. In this section, the authors analyze established and advanced design theories and methodologies in the framework of biological designs and illustrate their implementation through methodologies and examples. In particular, by expanding a

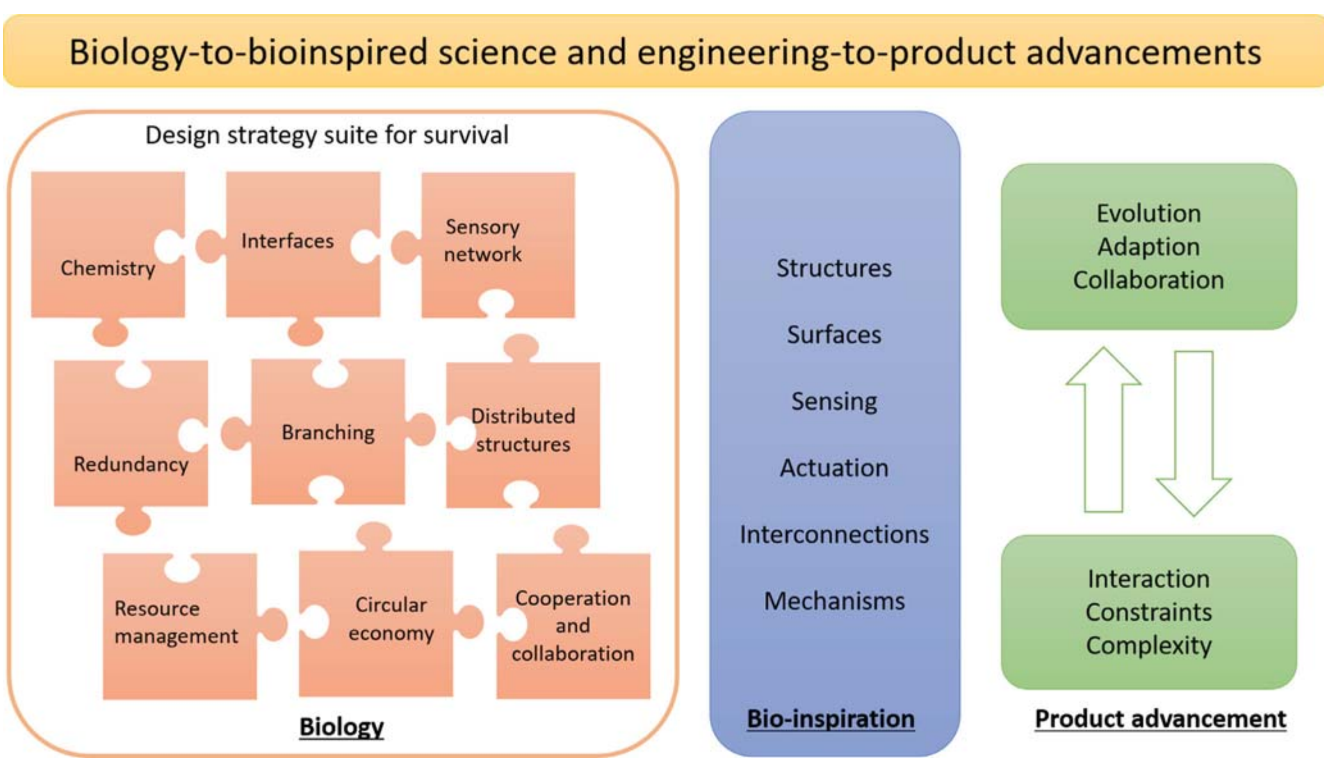

Fig. 1. Interrelation of biology - bio-inspiration - product advancement as a theme of this paper.

previous classification of the design theory and methodology (DTM) [226], the relevance of design-to-manufacturing (DTM) to biologicalisation is examined for five categories, namely design problem, solution, process, information, and knowledge.

2.1. Bio-inspiration-related design theory and methodology

Design Problem - DTM in this category can navigate designers to depart from an ill-defined problem statement and arrive at a concrete problem as the design target. In the context of product design, problem formulation involves translating vague customer needs into explicit functional requirements and design constraints. In comparison with regular problem formulation, biologically inspired design (BID) involves an additional procedure of translating an engineering design problem into an analogous biological problem. Problem formulation in BID involves formulating a design problem, decomposing the design problem into sub-problems, reframing the design problems in biological terms, and searching for relevant biological problems [207]. Some design methods have been developed to facilitate the above process such as natural language processing [206], Four-Box Method [99], the biologically meaningful keywords [46], and more.

A product design problem tends to be triggered by unmet and/or new customer needs. Likewise, a biological system develops a unique biological solution to fulfill its evolutionary needs such as survival, reproduction, and prosperity in space and time. However, few efforts have been devoted to investigating the analogy between customer needs regarding advanced products and the evolutionary needs of biological systems. A practical challenge is that the design methods that are commonly used to solicit customer needs (e.g., focus groups, surveys, design ethnography, and user-generated content), cannot be directly used to interpret the evolutionary needs of biological systems.

Design Solution – DTM in this category can support designers to generate, improve, and selecting design solutions. After a design problem is mapped to a biological problem, the biological problem leads to an array of naturally existing biological solutions. Underlying principles are then extracted from the biological solution, followed by adapting the principles to an advanced product. In correspondence to the decomposition of the design, the problem is the physical integration of multiple sub-solutions into a whole system. Hence, the interface between various components constitutes a typical challenge for advanced products. In contrast, most biological systems appear to be whole 'monolithic' systems without distinctive boundaries and joint interfaces between adjacent components. Such inspirations are especially applicable to the engineered system-of-systems (SoS).

For solution generation, design by analogy (including BID) is a classic method for creativity-based design ideation [226]. Some methods have been developed to facilitate the mappings between engineered and biological components [163]. Besides, analogy-based synthesis (including BID) plays a critical role in computer-based design synthesis for solution generation [42]. To solution improvement, TRIZ (from the Russian phrase Teoriya Resheniya Izobreatatelskikh Zadatch) is a typical modification-based design method [226], which can be used to improve an existing solution by resolving its inborn contradictions. The novel integration between TRIZ and BID leads to BioTRIZ [238], the core database of which is constructed based on biological phenomena instead of artificial inventions (i.e., patents). Besides, a design solution can be continuously optimized through various bio-inspired optimization algorithms. For solution selection, design decision-making involves selecting the best solution among multiple alternatives. Relevant methods for solution selection include Pugh's Matrix and Analytic Hierarchy Process. Due to the divergent nature of BID, relatively few efforts have been devoted to decision-making problems enclosed in the BID, for instance, how to select the best solution analogy.

Design Process – DTM in this category can facilitate designers to conduct design through a systematic process. Multiple generic design processes have been proposed. A typical design process is characterized by the alternation between divergent thinking and convergent thinking. The same pattern is equally applicable to biologically inspired design. A generic design process can be tailored to accommodate biological inspirations, being situated in a particular design scenario. The systematic design process by Pahl and Beitz, which is one of the most widely practiced design processes, has been adapted to enable BID [164]. The Function Behaviour Structure (FBS) ontology has been adapted to structure the BID process for smart product design [37,135]. On the other hand, multiple specific BID processes have been prescribed [100].

It should be noted that, in practice, a product design process is rarely conducted linearly directly from upstream to downstream domains. But rather, the process often involves back-and-forth iteration, negotiation, and collaboration that engages numerous stakeholders. A bio-inspired design process is by nature more challenging because it involves not only inter-disciplinary collaboration between designers and biologists but also cross-domain iterations between engineering and biological domains. Both factors have significant impacts on the effectiveness of the bio-inspired design. Furthermore, a product design process can be initiated in light of both market competition and technological breakthroughs. Likewise, a bio-inspired design process can be triggered by not only known biological solutions out of natural selection but also new scientific discoveries of unknown biological mechanisms.

Design Information – DTM in this category can facilitate designers to organize, enrich, and manage design information concerning a product's functions and attributes. Firstly, certain design methods can be used to capture information about biological systems. For example, the function, behavior, and structure (FBS) design ontology can be adapted to capture the functional information of biological systems [236]. Secondly, certain biological methods can be used to analyze the attribute information of engineered systems. For example, design patterns extracted from biological systems can inspire the design of distributed computing systems toward higher robustness and adaptability [10]. Lastly, certain information theories can be used to measure both the genomic complexity of biological systems [5] and the design complexity of engineered systems [218].

Design Knowledge – DTM in this category can support designers to extract, represent, and retrieve design knowledge. The importance of knowledge in product design cannot be overstated. Through biological examples, the knowledge base of design can be greatly expanded to include knowledge about both advanced products and biological systems. Bio-inspired knowledge constitutes an important source of design knowledge [43]. Some efforts have been devoted to facilitating the knowledge transfer between biological and engineered systems at different abstraction levels [195]. Knowledge-based CAD systems have been proposed to support BID for cognitive, collaborative, conceptual, and creative design [82]. Computational tools have been developed to represent causality and perform analogous reasoning based on a database of engineered and biological systems [41]. The biological database can be coupled with a patent database to accelerate the search for suitable analogies [235]. Exposure to bio-inspired knowledge can enhance the effectiveness of design ideation [248]. The cross-domain knowledge transfer between biological and engineered systems, through the support of knowledge-based design tools (i.e., AskNature), can support designers to think outside of the box [234]. On the other hand, the undesirable phenomenon of design fixation can often be observed in BID [141], i.e., inexperienced designers are inclined to focus on specific features such as functionality and/or frugality and/or robustness in lieu of generic principles.

Fig. 2 illustrates a series of interrelated research inquiry subjects, listed as follows, which hinge on the overlapping between bio-inspiration with design theory and methodology. In the design domain, different design solutions are created purposefully by designers to address various design problems. In the biological domain, different biological systems survive against various biological problems. The opportunities of bio-inspired design lie in the bidirectional mappings between an array of mirroring entities (i.e., problem, solution, information, and knowledge) across the two domains.

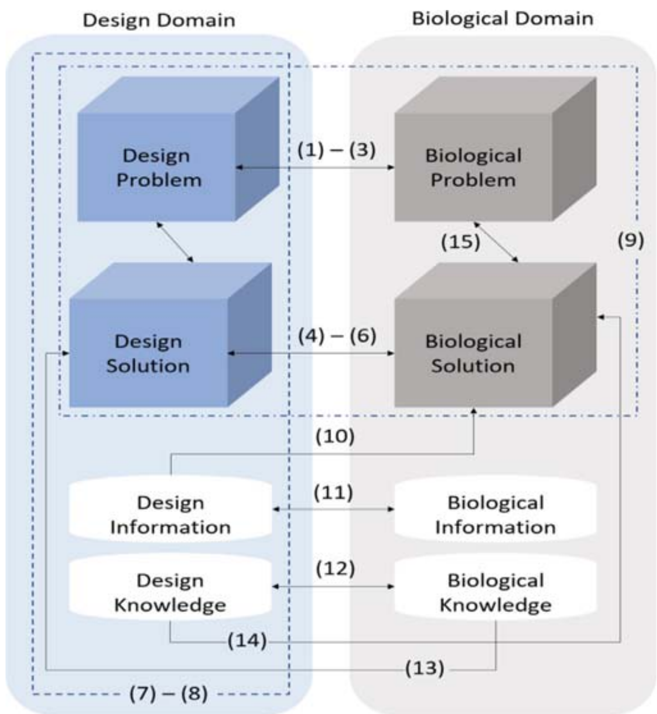

Fig. 2. Research questions in DTM for bio-inspired design.

1. Establish an analogy between design and biological problems;
2. Develop functional modeling of biological systems;
3. Establish an analogy between the customer and evolutionary needs;
4. Generate new solutions based on biological inspirations;
5. Improve existing solutions based on biological inspirations;
6. Make informed decisions to select a solution or analogy;
7. Adapt a generic design process to fit biological inspiration(s);
8. Conduct a biologically-inspired design process in different patterns (e.g., collaborative, concurrent, and iterative);
9. Follow a specific design process to formulate BID problems and generate BID solutions;
10. Analyze functional information of biological systems;
11. Apply information theories to analyze, and compare biological and engineered systems;
12. Transfer knowledge across biological & engineering domains;
13. Understand the impacts of bio-inspired knowledge on design ideation and design fixation;
14. Validate design knowledge through biological systems;
15. Search relevant knowledge in a biological database.

2.2. Bio-inspiration for different facets of advanced products

A library of designs in biology can benefit product design in multiple ways. Fig. 3 illustrates how different facets of biological systems are mapped to the corresponding facets of advanced products. Biological inspirations can be extracted with respect to how a biological system interacts with the natural environment, how a biological system adjusts its functions, behaviors, and structure over time, and how natural selection drives biological systems to collaborate, adapt, evolve, and be resilient as well as frugal. Such biological inspirations can be mapped to different facets of advanced products concerning how a product meets benchmarking against open competition, how a product manages its functions, behaviors, and structure, and how market competition drives a product to sustain and prolong its life cycle. Multiple specific facets of advanced products that can benefit from bio-inspiration are elaborated as follows.

On the other hand, the above mappings are not perfectly aligned along all three dimensions. Firstly, despite many similarities between market competition and natural selection (e.g., competition for resources, competition-driven selection, and feedback provision in competition), they have many fundamental differences. For instance, advanced products should be designed to comply with the human need for sustainability which is hardly considered by single species in the biological ecosystem. Secondly, both advanced products and biological systems have generations and life cycles. However, the natural selection of biological systems tends to span a significantly longer period than the market selection of advanced products. As such, the bio-inspired design between the biological system and advanced product has invisible boundary conditions. If such boundary conditions were not considered, bio-inspired design may easily fall into the trap of oversimplification.

Product Structure – Bio-inspirations can be gained in terms of how a biological component, sub-system, or system is structured to fulfill its intended functions. Here the notion of 'structure' is

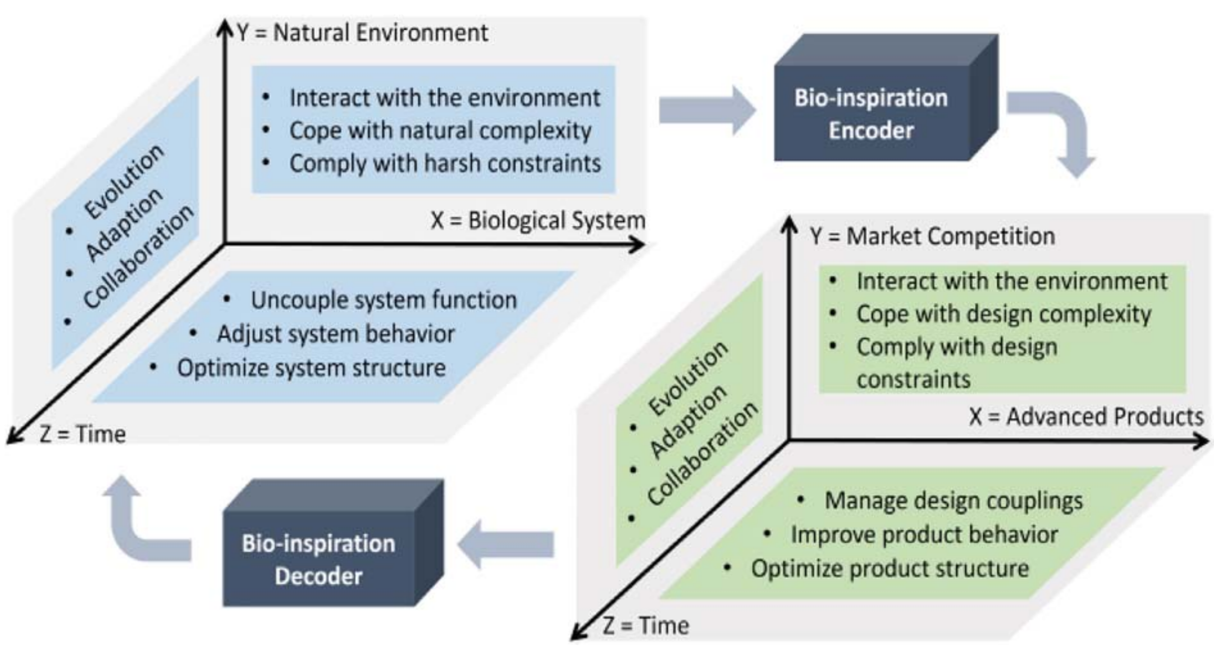

Fig. 3. Bio-inspired design for different facets of advanced products.

adopted from the FBS ontology, referring to not only individual design parameters (DP) but also the overarching architecture that integrates separate DPs. Firstly, an effective biostructure can be recreated and incorporated into an engineered system. For example, the muscular hydrostat of an octopus can be integrated into soft robots to achieve higher degrees of freedom and greater computing efficiency [128]. Secondly, inspiration can be gained from biological systems in terms of the physical integration of separate DPs. For instance, inspired by the skeleton and joint structure of animal legs, a multi-joint vibration isolation structure can be developed to achieve a high-static-low-dynamic stiffness [112]. Thirdly, some biological inspirations are relevant to the mapping between functional requirements (FR) and DPs. For example, the functional sharing of biological components, sub-systems, and systems, where multiple FRs are fulfilled by one single DP, can be leveraged to streamline design couplings [21]. Next, certain architectures of biological systems apply to advanced products. For example, inspired by the mound-building behaviors of termites, a desirable high-level structure can be decomposed into corresponding low-level rules on individual robots [244]. Lastly, with respect to structural optimization, for example, biological inspirations are useful for topology optimization and generative design in additive manufacturing (AM) towards desirable properties (e.g., lightweight) [61,260]. In particular, AM makes it possible to recreate many biological structures that are otherwise impossible to produce by traditional manufacturing technologies. For example, AM can be used to produce bio-inspired structures that are multi-scale [16], multi-material, and multi-functional [257], and to build an entirely soft robot that is structurally analogous to an octopus [242].

Product Complexity – Bio-inspirations can be gained in terms of how biological systems cope with various complexities. Design complexity can be interpreted as a system's uncertainty to fulfill its intended functional requirements [218]. This interpretation is applicable to both biological and engineered systems, the complexity level of which is determined by the demand for robustness against uncertain environments [51]. Many biological systems demonstrate extraordinary abilities to cope with complexities. For example, against an emergent evacuation scenario under life-and-death conditions (i.e., a particular form of dynamic complexity), ants can achieve incredible efficiency by uniformly distributing over the space instead of crowding near the exit [174]. Some biological systems can synthesize individual behaviors of relatively simple systems into complicated structures and sophisticated behaviors. For instance, army ants can construct a complex bridge using their bodies to cross forest-floor gaps, which can inspire the design of self-assembling systems [184].

Product Constraint – Bio-inspirations can be gained in terms of how biological systems comply with harsh constraints. Design constraints can be classified into input constraints and system constraints. The former and the latter constrain a system from achieving higher performance from its outside and inside, respectively. For example, an ant can lift a weight that is significantly greater than its body weight, which constitutes a vivid example of extending the boundary of system constraint. Against the extreme temperature in deserts (i.e., a particular form of input constraint), Saharan silver ants rely on a silvery appearance, which is composed of a dense array of triangular hairs, to enhance reflectivity and emissivity [204]. Therefore, biological inspirations can be leveraged to generate more constraint-compliant design concepts [136]. For instance, the path integration strategy of desert ants (i.e., integrating directional information by skylight compass and distance information by odometer), against the extreme heat constraint, can be used to navigate robots in outdoor environments [62].

Design constraints play a critical role in biologically inspired design, especially concerning solution generation. Changing constraints is an effective strategy for searching for relevant biological solutions [100]. On the other hand, it should be noted that not every natural constraint that shapes a biological structure is equally applicable to product design. Likewise, advanced products are constrained by many artificial constraints (e.g., economic and racial inequities, social taboos, and legal regulation) that are not known to exist in the biosphere. Hence, proper analogies between biological and engineered systems should be established concerning design constraints, possibly as a sub-task of problem formulation in biologically inspired design.

Product Cognition – Inspirations can be gained from biological systems to enhance product cognition that involves multiple facets such as memory, attention, spatial navigation, problem-solving, *etc.* Cognitive ability is especially important for smart products and autonomous devices. For example, the navigation strategies of desert ants (i.e., path integration, visual piloting, and systematic search) can be adopted to navigate mobile robots [127]; the decentralized problem-solving ability of ants can be transferred to a group of robots for cooperative transport [126]. Artificial intelligence and machine learning are growingly integrated into advanced products to interpret human language and learn unknown patterns. In the long run, it may be possible to develop 'living manufacturing systems' that are characterized by self-learning and self-cognition [34].

Product Collaboration – Bio-inspirations can be gained in terms of how biological systems collaborate. Such inspirations are especially applicable to the design of IoT devices, autonomous vehicles, and smart products. Biological systems of the same species can coordinate actions among peers for collective utilities that transcend individual abilities. The collective behaviors of social animals can be leveraged to design various swarm robots [30]. Inspired by the collective behaviors of insects, the teamwork effectiveness of robot colonies can be enhanced [169]. Principles that govern the division of labor in ant colonies can be used to facilitate task allocation in distributed robots [125]. Through a bidirectional mechanism, namely tandem running, an 'expert ant' can actively teach a 'novice ant' to locate food and a nest [78]. Inspired by the collaborative behaviors of termites in designing, optimizing, and manufacturing nests simultaneously, a generative multi-agent design methodology is developed for additive manufacturing [58].

In contrast, symbiosis refers to a partnership between different species of biological systems for reciprocal benefits. Symbiotic relationships can also be observed in engineered systems. Symbiosis can be interpreted as a particular kind of product-service system, where one product shares its functions with another product in the format of services towards reciprocal values. For example, through symbiosis, an Egyptian plover can provide a crocodile with a 'teeth cleaning' service [50] For the inspiration for product design, for example, the lichen symbiosis (between fungus and alga) can inspire the functional modeling of resource sharing in production [163]. The interactions among relevant stakeholders in manufacturing enterprises can be modeled as different kinds of symbiotic relationships [178].

Product Interaction – Product interaction concerns how and in what ways a product interacts with the target customer, peer product, and external environment. Design inspirations can be gained from biological systems in terms of how they interact with humans, peers, and the environment. For product-human interaction, for example, bio-inspired soft robots can be developed to achieve high softness and body compliance [120]. Unlike a typical industrial robot with a rigid body, a soft robot can achieve high degrees of freedom, absorb energies in a collision, and hence improve the safety of human-robot interaction [192]. Besides, biological inspirations can be leveraged to design more capable social robots with higher autonomy in the human-robot interaction [142], and more socially interactive robots with higher social intelligence [76]. For product-environment interaction, for example, some biological systems depend on camouflage strategies to interact with the environment. The basic principles of camouflage (e.g., disruptive patterns, resemblance to surroundings, and changeable skin coloration) have been adopted to design military uniforms, vehicles, and ships. The biological surface is an interface in the frontline of interactions between a biological system with an external environment. Inspirations can be gained from biological surfaces to design more/multi-functional artificial surfaces [148]. Inspired by the adhesive interaction between gecko feet and a vertical surface, a hybrid adhesive is developed to achieve a reversible attachment [130].

Product Adaption – Bio-inspirations can be gained in terms of how a biological system adapts itself to different environments. Such inspirations are especially beneficial for personalized products and reconfigurable systems. Adaptable design concerns design adaptability and product adaptability [88], both facets can benefit from biological inspirations. For product adaptability, for instance, inspirations gained from physarum polycephalum can be used to design a more adaptive transport network [224]. To design adaptability, for instance, by mimicking the biological process of how 'design information' is managed, a synthetic DNA-based approach can be proposed to support design for adaptability [113]. Along the direction of product adaption, it can be argued that even product innovation can benefit from biological inspirations. The three kinds of typical product innovations, i.e., continuous innovation, discontinuous innovation, and disruptive innovation can all find their analogies in biology, for instance, disruptive innovation is caused by a genetic mutation. Some innovation models existing in biological species and systems such as creative destruction and coevolution can also be observed in product innovations. For example, the innovation strategy of Apple Inc. can be largely attributed to its unique product ecosystem inspired by the biological ecosystem.

Product Evolution – Inspirations can be gained from the evolution of biological systems to model the evolution of advanced products. For example, the evolution of manufacturing systems can be modeled by analogy with biological evolution [64]. Biological evolution is triggered by natural selection and genetic drift (random fluctuations in the frequencies of alleles from generation to generation due to chance events) [190]. Similarly, product evolution can be triggered by market competition and demand shifts, i.e., a product must evolve continuously to meet benchmarking with other products and fulfill emerging customer needs. Different paradigms of evolution apply to product design in different fashions. Firstly, convergent evolution means the independent evolution of different species towards identical features. For example, birds and insects evolved parallelly toward identical wing structures. In the context of product design, convergent evolution can be exemplified by independent patents with identical working principles that are developed separately in different industries. Secondly, divergent evolution means that different populations of the same species diverge towards more or less distinct features. In the context of product design, for example, different customers tend to personalize the same hardware of smartphones divergently to accommodate different software applications (and their associated functions). Finally, coevolution means that the evolutions of two or more species are coupled with and influenced by each other. In manufacturing, for example, the coevolution between product design and manufacturing systems has been investigated [6,31]. In product design, for instance, concept generation can be modeled as the coevolution between design synthesis and analysis [134], and creativity can be triggered by the coevolution between the design problem and solution [59]. Fig. 4 presents a concept graph that illustrates how biological inspirations extracted from different species of ants can benefit different design facets of advanced products (i.e., Mars Rover and robot vacuum cleaner).

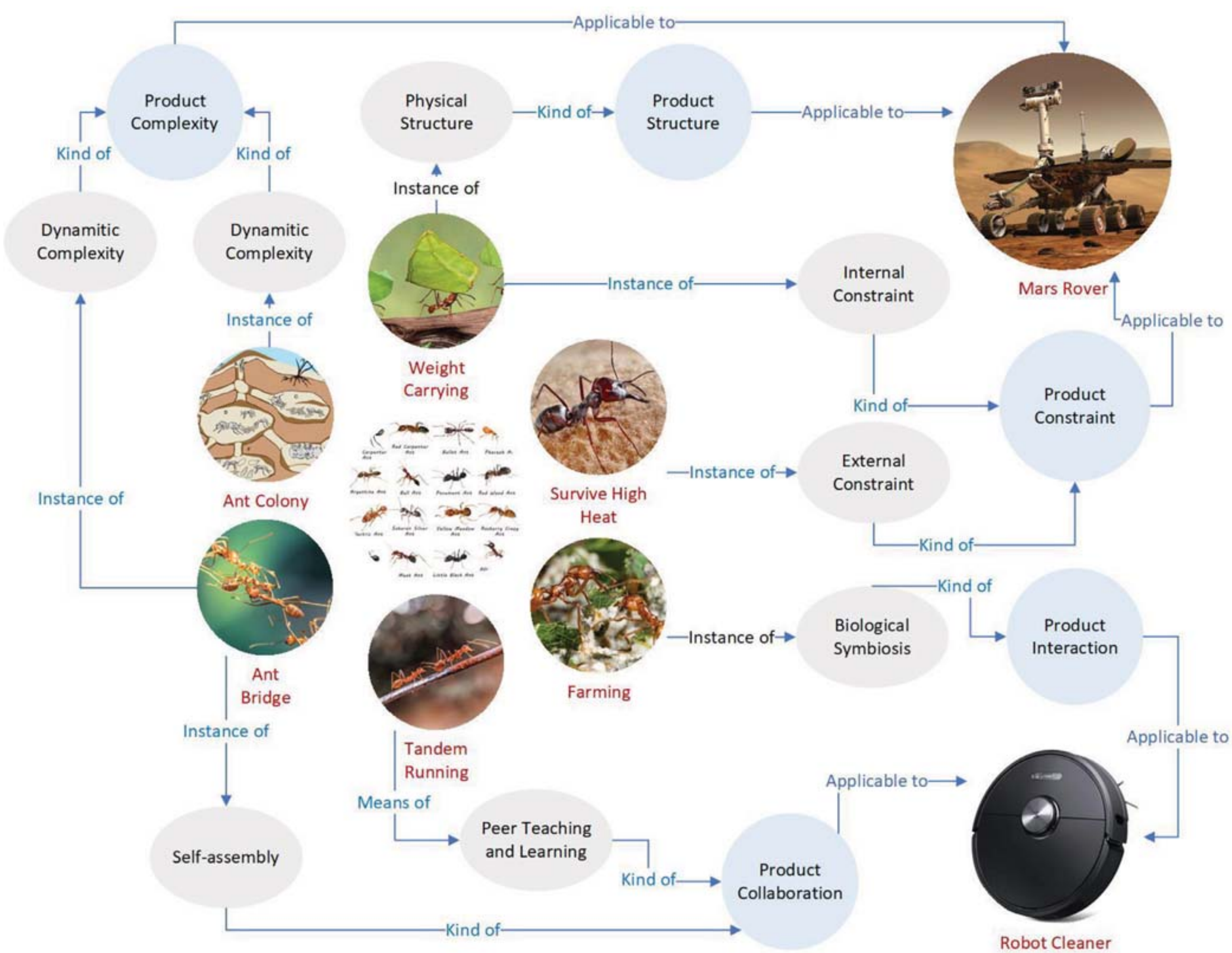

Fig. 4. Concept graph of biological inspirations gained from ants.

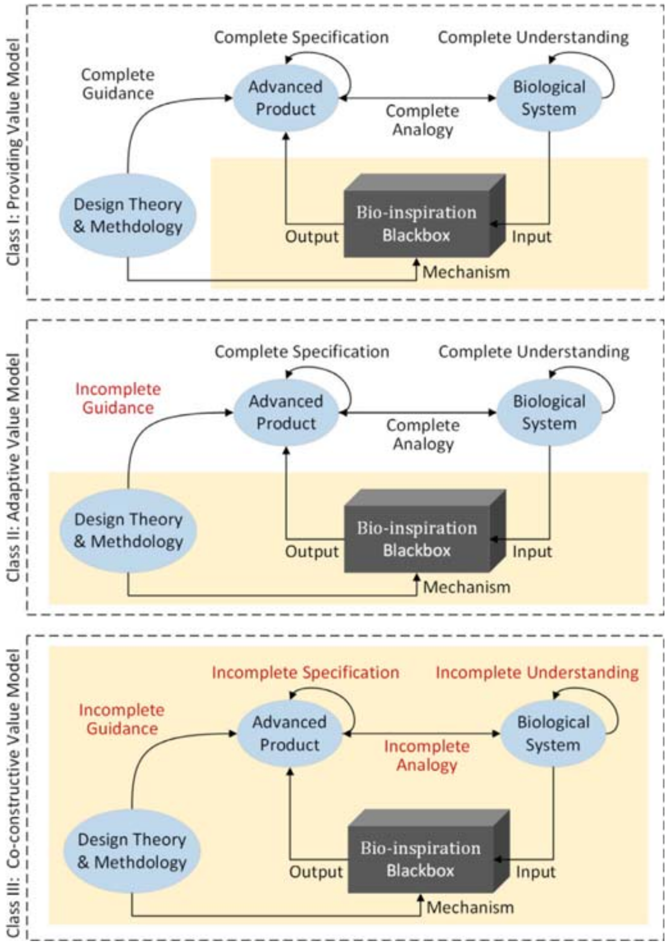

Fig. 5. Design value creation models of bio-inspiration.

2.3. Values and opportunities of bio-inspiration for product design

Inspired by the value creation modeling of the Emergent Synthesis [231],Fig. 5 shows three classes of value creation models of bio-inspired methodology for product design, where the highlighted areas in yellow represent the potentials of value creation.

1. **Class I**: bio-inspiration is conducted with complete product specification, *a complete understanding of biological systems, complete analogy, and complete guidance of DTM*. New values can be created by mapping a specific facet of biological systems to that of advanced products.
2. **Class II**: bio-inspiration is conducted with complete product specification, *a complete understanding of biological systems, and a complete analogy. However, no relevant DTM can be followed to guide the bio-inspiration process*. Therefore, new values can be created by developing new theories and methods to guide practice. This class of value creation models highlights the focus of this section.
3. **Class III**: bio-inspiration is conducted with incomplete product specification, *incomplete understanding of biological systems, incomplete analogy, and incomplete guidance of DTM*. In this challenging scenario, new values can only be co-created through abductive, iterate, and interdisciplinary design endeavors.

Based on the above discussions, it is crisply clear that the driving force of bio-inspiration has enormous potential to enhance multiple facets of advanced products through the support of design theory and methodology (DTM). Multiple facets of advancements primarily are observed in delivering functions, robustness, and resilience to components and systems, respectively. Modern product design is being simultaneously reshaped by other technological forces. It is, therefore, necessary to continuously adapt relevant DTM on a holistic account of the convergence between bio-inspiration with other ongoing and emerging forces such as I 4.0, digitalization, and artificial intelligence.

Two key design principles of I 4.0, i.e., interconnectivity and decentralization [101], can both benefit from biological inspirations. For example, many social insects and animals are characterized by decentralized individual behaviors that result in collective values more than the addition of parts. The convergence between bio-inspiration and I 4.0 can lead to opportunities such as utilizing biological inspirations to enhance the decentralized decision-making of manufacturing systems, connecting engineered systems with biological systems toward a more inclusive Internet of hybrid things, and integrating multiple bio-inspired systems towards a more capable system-of-systems.

In the digital era, the process of product design is becoming more digitalized and data-driven than ever before. The two sweeping trends of digitalization and biologicalisation can join forces to reinforce product design. Some digital design tools and data-driven design solutions, which are initially developed for advanced products, are equally applicable to biological systems. For instance, a digital twin can be used to construct bio-intelligent systems [154], and simulate patient conditions for precision medicine [48]. The convergence between bio-inspiration and digitalization can empower designers to model the dynamic interaction between biological and engineered systems, digitalize the environment where biological systems live and advanced products function, and predict the future evolvement of engineered systems through data-driven approaches.

Artificial intelligence (AI) is increasingly incorporated into product design. Many technological breakthroughs of AI are initially triggered by biological inspirations [74,223]. For example, various artificial neural networks are inspired by the biological neural networks of animal brains [54]. Bio-inspiration can be converged with AI in two directions. On the one hand, AI can be incorporated into various smart products, industrial robots, wearable devices, and autonomous devices to enhance product intelligence and autonomy. On the other hand, AI can be employed to facilitate the biologically inspired design process, for example, by developing recommender systems to recommend relevant biological knowledge to designers, constructing a knowledge graph to represent relations among cross-disciplinary entities, developing generative design tools that can facilitate designers to locate the most applicable biological solutions, and automatically enriching existing databases such as AskNature and others [57].

3. Biological designs: attributes and value propositions

Following the inquiries and thesis discussed above, a question could be asked on why biology manifests so many designs in their attributes and what values are gained from the products. Attributes such as size, form factors, hierarchical integration, integration of heterogeneous materials in various aspect ratios, manufacturing processes, coding signatures of these designs in markers such as DNAs and fingerprints, communication channels within a living body, among the living bodies of the same species, among species in each ecosystem, and all living species and their environments, and many more. To answer the above question, it could be argued that for biology to survive and thrive materialistically, three important value factors or pillars are critical namely functions, resilience, and frugality. These three physical attributes are manifested, inside the body of one animal or among their collective, by the application of various design attributes and their effective interactions with the environment. Illustrative examples of such value factors are 1) tessellated and anisotropically textured sharkskin [56,147] with the functional requirement of reducing the hydrodynamic drag, 2) the ability of sharks to travel hundreds of miles across the oceans to address the climatic changes, and at the same time have the ability to maneuver swiftly as a large body of shark gets attacked by the predators for resilience, and 3) to keep the surface clean during operation and the whole body of shark being biodegradable as the corpse degrades at the bottom of the ocean providing food to the microbes as a part of the circular life cycle in the living environment. Numerous other such examples can be quoted including designs of trees, leaves, organs of living beings, colonies of ants as discussed above, communication among trees and birds, and many more [146].

The following sections describe the contextual thesis, understanding, and illustrations of the three value factors of bio-inspired designs, including multifunctionality, resilience, and frugality endowed partly and fully due to the designs in biology in the context of products and production science and engineering.

3.1. Design for multifunctionality

Multifunctionality is defined as the combination of physical and chemical characteristics manifesting the measurable more than one functional behavior in the species' (biology) performance in the given space and time as a reaction to internal and/or external actions. Multifunctionality is widely manifested in all biological species and for specificity, authors have chosen the human species to discuss design−functionality correlation.

Out of over eight million surviving species, humans are one of the best examples where designs are manifested along with the combination of materials to deliver multiple functions. These functions include optical and auditory sensing for actuation for movement, neurological coordination of actuation of different body parts across the length scale boundaries, and many others. From the design perspective, it is noteworthy that how in the human body as a system, functional subsystems are partitioned and positioned in certain spatial coordination. Along with this, the key design structures are used effectively and repetitively across the body, such as 1. branching for bones, blood vessels, and neural communication; 2. the heterogeneous organization of cells and muscles, anisotropic fibrous structures of the bones, and the organization of proteins in DNA strands; 3. combination of hard and soft matters to achieve hardness and toughness in teeth [261], hardness and flexural strength in bones [69,187], hardness and impact strength in the skull [252].

A typical product designer is looking at a product through multiple facets including topography, the architecture of the bulk, the use of materials, and available choices of manufacturing processes, but with an intended goal of delivering function(s) to a product for purposefulness during either delivering next generation of the product or advancing existing product by solving a specific problem(s). (Framework of this is discussed in the section before.) For the designer, multiple functions demonstrate a synchronized interplay in space and time during the integrated system's operation. Examples of such products and their designs for multifunctionality can be seen in electric vehicles, drones, handheld electronic devices, remote surgical instruments, and others. With the advancement of mechanical, electrical, acoustic, thermal, and optical disciplines through the fundamental understanding and ability to integrate these functions by using manufactured components, design science is driving advanced designs through the integration of functional subsystems. To understand and develop a biological model analog of such a multifunctional system, one can visit human (or another species) anatomical design as a wholesome example.

The combination of symmetry, topographical optimization, time sequencing, sensing, signaling and actuation, hierarchical integration of interrelated and interconnected building blocks, integration of functionally active materials, and their seamless interplay manifests a unique anatomical design model of a human for adaptation and reproduction (Fig. 6). Alike some of the latest product designs, the human body's design combines optical, electrical, mechanical, acoustic, thermal, and other functional signals and related subsystems. In this biological model, functions provide design rules for components of subsystems. For example, in the design of an eye and ear as subsystems for visible wavelength region and auditory frequencies, respectively, the selection of components such as retina and cochlea, respectively, have used rules of symmetry, topography, signal-surface interaction, signal decoding, and more geared for the functions (and signals) of interest. Subsystems are built with the integration of components using structural features discussed in Fig. 6. The design of components for a subsystem, placement, and interfacing of these functional components in a subsystem, and the operational positioning of these subsystems in a human anatomical model demonstrate an overall methodology for delivering higher order of multifunctionality working in synchronization. These hierarchical design integrations are intimately complemented by functionally active materials, their placement according to the design, and their ability to grow and sometimes regrow aided by biomanufacturing processes. The biomanufacturing processes use resources selectively and frugally based on one human lifetime, geographical location, and biodiversity.

Fig. 6. Comparison of analogies between human anatomy and autonomous vehicle for multiple functions.

Such hierarchical integration of subsystem functions and active materials for a system operation is seen in the newer product designs. However, these products are built using asynchronous manufacturing processes and aided by resources provided largely by global supply chains, unlike local supply chains for the 'human body'.

To address the key requirements including delivering more functions per unit volume and per unit product price, products in the synthetic world are increasingly demonstrating parallels with the biological systems [34,36,44,118,140,147,148,189,210,216,233,247]. Fig. 6 establishes such parallels in the human system and its subsystem as the bio-inspiration decoder and autonomous vehicle. As it is evident that in the bio-inspiration decoder, bio-inspired subsystem functions (coupled or decoupled) and their adaptation to various natural environments over time have yielded current designs of subsystem functions including optical, acoustic, electrical, thermal, and mechanical. Alike in the bio-inspiration encoder, in an autonomous vehicle, one can see the advanced product functions being partly a result of market competition and over time growing consumer demands resulting in subsystems that are also paralleled with biological systems. These multifunctional subsystems have unique common attributes in biological and synthetic worlds where the functional subsystems sense and actuate in space and time. Then they interact and inform and synchronize using their data between and/or among each other, using the central communication nervous system, as they interact with the surrounding other systems and environments. The designs of subsystems have commonalities including the proportionalities of length scales with the receiving signals and the reaction in the form of actuation, surfaces of the subsystems compliant through the adjacent and interacting subsystems as well as the environment, the transmissions of signals through the anisotropic branched pathways, and the choices of materials which are compliant with the signals and environments. Table 2 illustrates the above-discussed salient points in a comparative chart of functions for humans and autonomous vehicles (AVs).

Despite the large parallels in the multifunctional subsystems, today's biological subsystems and synthetic subsystems diverge in their response to calamities for resilience and their frugality report card. A few of the notable reasons for this diversion are pointed due to the ability of these designs to heal and regrow routinely (e.g., daily), the source and the type of raw materials applied for the reconstruction and/or maintenance, and the ability to manufacture and remanufacture at a given site, at a given time and for a given purpose.

Table 2
Analogies between a human and autonomous vehicle for optical, acoustic, thermal, mechanical, and electrical signals and sensing.

Analogs Functionality	Human	Autonomous vehicle
Optical	Eyes: human eye design allows for the light in the visible spectrum to be collected through the surrounding which is focused through the lens on the retina for recognition.	Cameras and LIDARs: Relies on multiple cameras to capture the live visual images of the surrounding environment along with 3-D laser scanning for distance perception.
Acoustic	Ears: design of the human ear tunnel and diaphragm that allows to receive and collect 20–20 kHz [202] sound waves.	RADAR and SONAR-based detectors for monitoring the surrounding traffic and communicating with nearby vehicles.
Thermal	Skin: skin surface and sub-surface receptors [7] monitor the temperature on the outside of the body. Skin also allows for maintaining the temperature via homeostasis.	Thermal management in vehicles is typically achieved at the battery/engine interface by utilization of a fluid-based lubrication system, radiators, and exhausts.
Electrical	The sensed data (auditory, visual, and other) is transmitted to the brain through the network of neurons and nerves where the data is stored and analyzed for perception and decision-making	The sensed data (auditory, visual, and other) is transmitted and analyzed to the computer/AI interface for decision-making and guidance through a network of electronic circuits
Mechanical	Actuation: any action (movement, locomotion, etc.) is achieved through the hierarchical design of human tissues, muscles, and their coordinated attachments to bones. and bone joints. The movement is achieved by converting the chemical energy stored from the consumption of food to mechanical energy.	The mechanical energy is generated through the conversion of chemical energy (batteries for electric vehicles, burning of fuel) into mechanical energy for appropriate action/movement

Though it is noteworthy that over the multiple industrial revolutions, from I 1.0 to I 4.0, as multiple functions and materials have been integrated into the products, future directions for industry 5.0 and human-cyber-physical systems [139,160,215,240,262] would call for addressing the resilience, and frugality requirements [102] to complement multifunctional product designs and learn from the biological encoder. The applicability of strategies for multifunctionality to the manufacturing of advanced products is further illustrated in Section 4.

3.2. Design for resilience

Resilience is manifested in biology at the component level, subsystem level, system level, and system of systems level [146]. It is seen that resilience is achieved through the physical and chemical properties of the materials, manufacturing processes, and equally importantly design architectures. Resilience is defined as 'the intrinsic property of a system to resist, and/or recover from, and/or adapt to a new and improved state in a time much smaller than the overall lifetime of the system, under known unknown or unknown stochastic or random perturbation(s)' [146]. The design strategies applied in biology have been registered to be a collective combination (as represented in Fig. 7) that operates in tandem including 1. passive structures to protect and preserve the integrity of the system, 2. applications of the sensor(s) to monitor that integrity, 3. the use of redundancy of structures across the length scale boundaries to retain and advance the overall system robustness during perturbation(s),

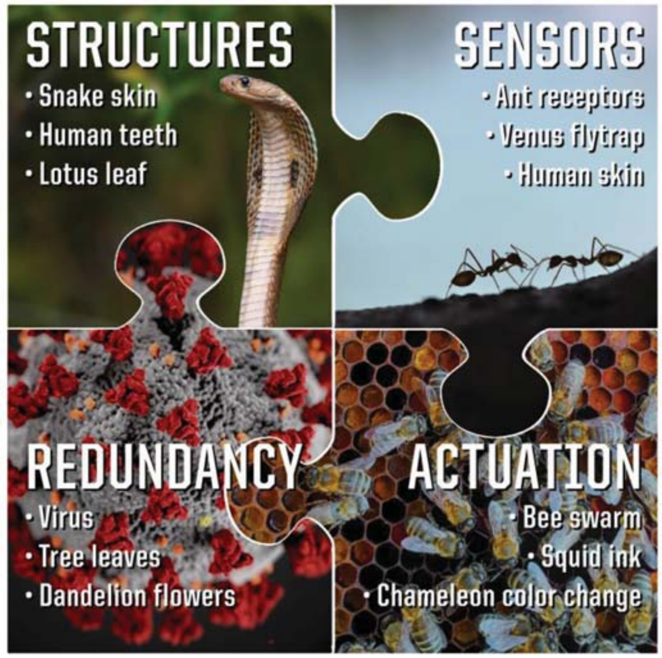

Fig. 7. Illustration of four combinatorial strategies to achieve resilience along with representative biological examples.

and 4. applications of actuation to edit/repair the undesirable variations caused by the perturbations.

In modern production, out of the above 4 strategies, to achieve intelligence and smartness, we have started to acquire the combination of all four strategies. However, the combination of these four strategies in state-of-the-art manufacturing creates inordinate amounts of data, a large number of interfaces, and a substantial footprint of various forms of waste. Unlike the state-of-the-art, in biological systems, the concept of 'data' is seamlessly integrated into the communication networks of a highly integrated natural system with heterogeneous signals, the interfacial integrity is managed by functional redundancy and every component of the biological system is a part of true circular survivability (economy). The following examples illustrate the above discussion on achieving resilience through biological design structures.

A structure is defined as topographically optimized features biology has applied at the surface and/or bulk of a functional subsystem or a system. Examples of the structures are textures, anisotropic fibrous structures, hierarchical organization of building blocks, and others [146]. Biology has used such structures effectively to either manage the adversities of the environment and/or overcome perturbations caused due to adversities. Structural designs such as spike proteins on a coronavirus, architectural designs fibrous matrix in a bone, and surface textures that are organized hierarchically on a ventral skin on snakes [16] to manage friction, wear, and locomotion as well as refresh the damaged surface are few of the example of structural designs biology has exploited actively at functional interfaces and beyond. The following paragraph illustrates salient points through the example of the ventral scale of a python regius snake.

Example-1 (*resilience – structures - locomotion in harsh environments*): Snakes represent a unique case study among reptiles as they have no limbs and could be seen as soft robot analogs. Design architectures of snake skins in various terrains across the world including the physical structure of the surface and the subsurface as well as the chemical pigmentation allow them to be resilient for survival [185,209,225]. A common feature among all the snakes is the presence of scales (tessellations) across all their bodies as shown in Fig. 8. The shapes and sizes of the scales vary based on their position on the body (e.g. head vs. tail or ventral vs. dorsal) [3,52]. Ventral snakeskin scale structures are typically hexagonal and are oriented perpendicular to the axial direction of the snake [4]. These scales

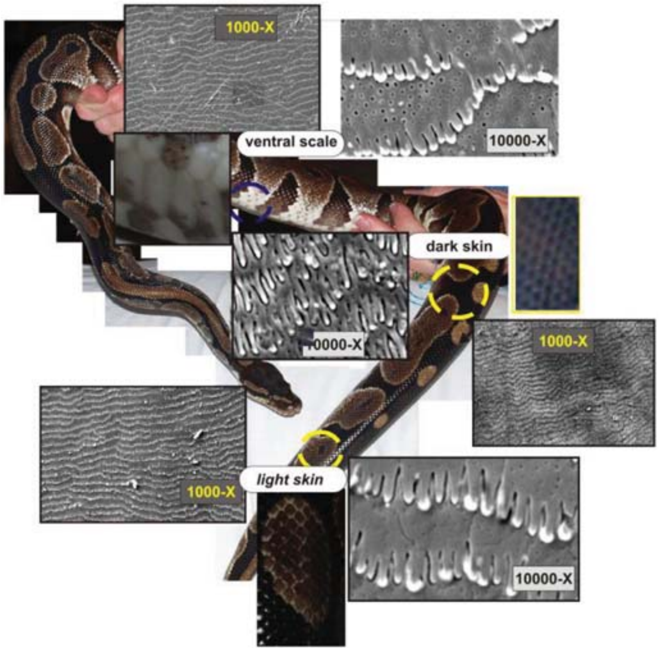

Fig. 8. Scanning Electron Microscope (SEM) micrographs from ventral and dorsal (light and dark colored) scales of *python regius* snake. Image reproduced with permission from [2].

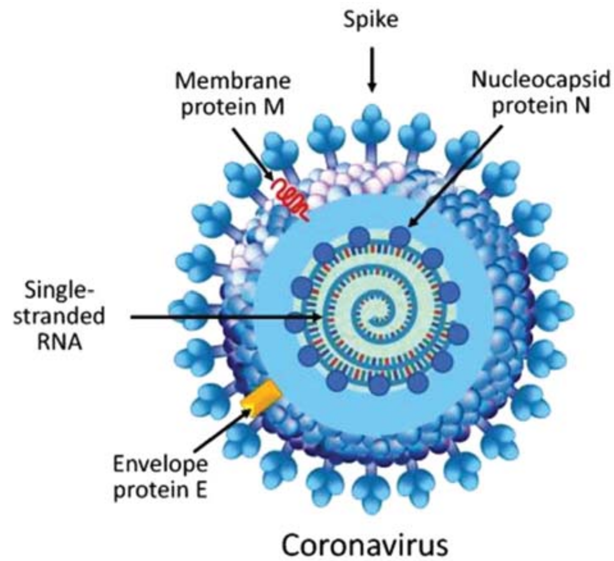

Fig. 9. Schematic structure of SARS-COV-2 coronavirus showing various component proteins and their design architecture. Image reproduced under Creative Commons Attribution 4.0 International License from [188].

further have micro-scale denticulations pointing towards the tail of the snake to manage the points of contact during movement [1,122,227]. When snakes move forward (using muscle movement), the locomotion is controlled by the interaction between the surface and the combination of macro-scales with micro-textures. The anisotropic micro-texture in combination with hexagonal scales allows the snake to adapt to various terrains and move efficiently in the forward direction only without slipping backward [94,253] thus allowing for robust locomotion irrespective of the changing terrain. Unlike where the ventral scales are typically in contact with the rough terrain, the dorsal scales are typically visible to the predators and the environment. The pigments on the dorsal scales of the snakes are responsible for the coloration. It is commonly observed that the color of snake species changes based on their primary habitat (e.g., snakes living in forests among tree leaves are green in color while snakes living in deserts have yellow and brown scales), suggesting its importance in camouflage for survival from predators. As snakes grow in age, over time, they also molt their skin which is thought to allow for their growth as well as replenish worn-out and microbially contaminated old scales. Shedding of the snakeskin is observed to be an effective way to maintain the freshness/health of the skin for continued operability [209]. In summary, the snake's ventral, and dorsal scale architectures, over their lifespan, endow them with abilities to adapt to their environment through the precision of locomotion, survival through camouflaging, and at the same time dynamic adaptation over their lifespan as a system and be resilient.

Example-2 (*resilience – redundancy- effectiveness of transmission*): Viruses are infectious particles that rely on their simple yet unique design structures for their activation and operation lifetime. Virus particles (also known as virions) primarily consist of a genome sequence (either DNA or RNA) encapsulated by capsid protein structures [40,239]. In addition to capsid proteins, certain families of viruses (including coronavirus) also contain an additional envelope. Fig. 9 shows the design attributes image of the SARS-COV-2 virus particle [188]. The viral envelope is made up of a lipid bilayer and contains binding proteins those control and mediate the interaction of viral particles with host cells [239]. Viruses are unable to replicate themselves and need a host cell to carry out their function. Since the virus particles require a host cell to function, infecting and infiltrating the host cell is a critical function for survival. The chief design attributes of enveloped virus particles are spike proteins (S) along with envelope proteins (E) and membrane proteins (M) [68]. To enter the host cell, a virus particle must first attach itself to the host cell. This is controlled by the S-protein which mediates the interaction between the virus particle and the receptor cells in the host. The symmetric and distributed arrangement of S-protein structures along the envelope provides multiple pathways for probabilistic host-virus attachment thus increasing the resiliency. Once attached, E and M proteins are then responsible for binding with the cell and infiltrating the cell machinery to activate and replicate. During the replication process, the genome sequencing units can introduce random or responsive errors to alter the virus composition structure. This results in the mutation of the viral sequence. In the wake of adversity, such as antiviral drugs, the forced mutation allows viruses to develop a viral strain that is resistant to the action of the drug and remains infectious [28,193,217], thus contributing to the resilience of the virus. It is noteworthy that at the time of writing this paper, the coronavirus pandemic is still ongoing due to different mutated strains of the SARS-COV-2 virus with varying degrees of transmissibility and fatality [124].

Example-3 (*resilience – sensing – collective behavior*): Sensing forms a crucial pillar for achieving resilience as it is critical to sense environmental changes to respond to them while limiting disruptions. It is not only important at a component level, for example, when a chameleon changes its color by sensing the environment to achieve camouflage, but also at a system level where inputs from multiple sensors at individual component levels can be meaningfully applied for yielding a robust system. Eusocial insects such as ants rely on olfactory sensors for sensing and tracking odors (Fig. 10). Ants use the two antennae to track scents [60] through odorant receptors (OR) by binding with odor molecules. The sensed information is conveyed to the brain through odorant receptors neurons (ORNs) [53,213] for taking appropriate action. Foraging ants or other insects such as fruit flies utilize odorant receptors to track food [84]. As a system (a colony of ants), the sensors are also critical to communicating between individuals and also to keeping track of movement by sensing pheromones or other chemicals [60]. As an example of resilience, ants trail, in the wake of disruption, an ant colony can sense and detect the environment to get back on track [153]. The roles among ant colonies are also dynamic and distributed which can change and redistribute in the wake of disturbance to maximize the output of the ant colony [11,86]. The tracking and movement of multiple ants on the same trail can be thought of as an example of vehicle platooning which is also used by large transport vehicles such as trucks (including autonomous vehicles) to increase their collective fuel efficiency. Besides

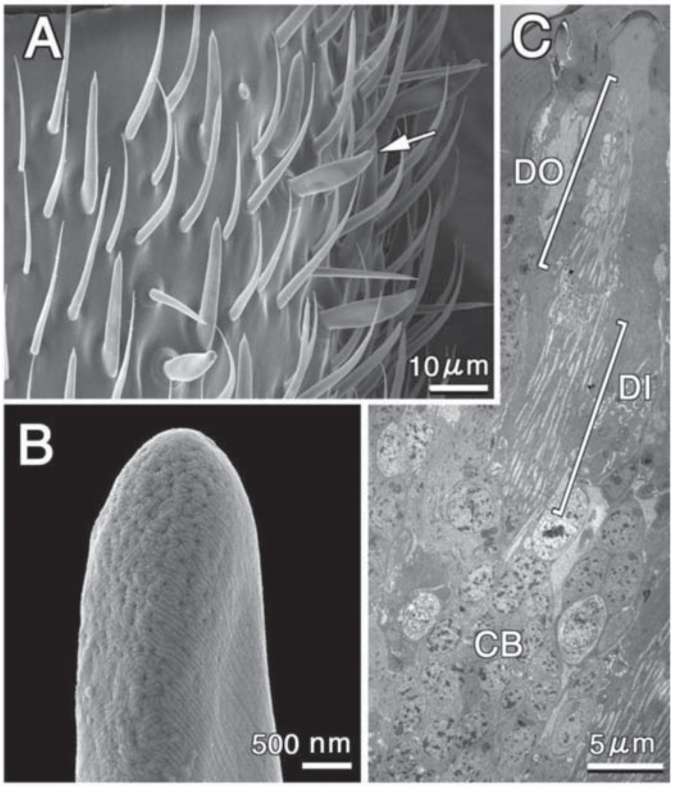

Fig. 10. (A) Scanning Electron Microscope (SEM) micrographs of sensilla on the antenna of ant *Camponotus japonicus*; (B) high-resolution SEM images of individual sensillum; (C) cross-sectional Transmission Electron Microscope (TEM) image showing DO- dendritic outer segments; DI- dendritic inner segments; CB- cell bodies of the receptor neurons. Image reproduced from [173].

food gathering and tracking, the chemical signaling pathways in ants and other insects also serve as communication methods for mating and reproduction.

Example-4 (*resilience – actuation – collective function*): Similar to the example of ants discussed above, several species exhibit distinct behavior as a group based on collective interaction amongst individual species but at the same time integrate redundancy to increase reliability for resilience. Such behavior at a system level is commonly referred to as 'swarm behavior' or 'swarm intelligence' [203]. Examples of such systems include a flock of birds migrating during changing seasons, a school of fish moving together in water streams, a swarm of bees swarming into different nesting sites, and others [138]. The uniqueness among all these examples is the fact that the collective intelligence of the group (system) controls the adaptive behavior which would not have been possible at the individual species level and integrate distributed redundancy to enable the demonstration of resilience at the system level benefiting back individual [47]. Such swarm intelligence approaches inspired by biology are being applied in the field of robotics and other unmanned vehicles/drones. Using sensing and communication between the individual units/species, the whole group relies on collective information to navigate through obstacles and/or to optimize their movements [111]. Much like in biological swarm systems, this behavior is resilient to disruptions by adapting and responding to the dynamic changes in their environment collectively, even though each individual species is not most informed to make the best decision collectively they yield far superior behavior.

Specific to honeybees, swarming is associated with the formation of a new nest/colony of bees [199] when the existing nest is exceeding its capacity. In this process, queen bees along with about a third of the population move to a nearby tree (temporary location) while a new potential nesting location is being scouted. During this process, few 'scout' bees (fewer than 5 percent) hunt for new possible nesting locations [87,199]. The decision-making for the new location process

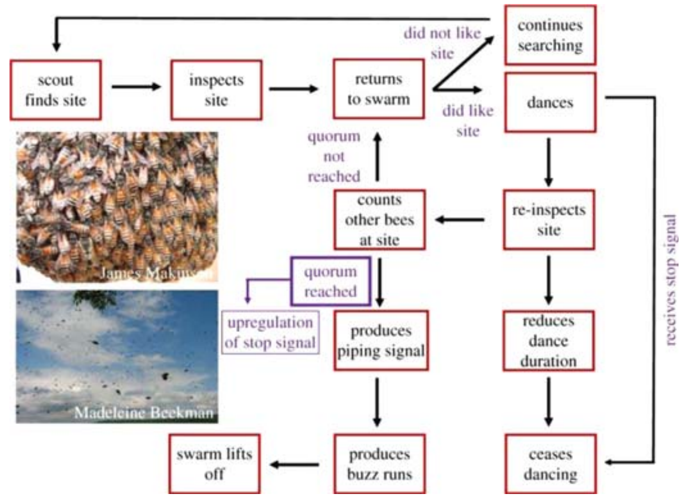

Fig. 11. Mechanism of swarm migration and decision-making in finding new nesting sites for bees. Reproduced with permission from [18].

involves a decentralized approach where the queen bee does not have control over the decision [77]. Additionally, the presence of multiple scout bees means that there is in-built redundancy for the potential nesting sites as fallback options for resilience [18,77]. Several key attributes of the bee swarm enable the resilience of the collective system. Through the signaling mechanism involving dancing (physical movement), potential sites are shared/advertised to other bees for recruitment, and eventually, a collective consensus is reached [20]. Once the decision is made, the entire swarm of bees moves to the new location. During the movement, only a few individuals know the destination and the remaining bees (including the queen) are ignorant of the new location. Relying on movement, signaling, and sensing mechanisms, these informed bees can navigate the whole group toward the new location [87] (Fig. 11).

In summary, it is observed that resilience is an integral consideration in all biological designs across the hierarchy which makes the bio-inspired design platform an important learning platform to advance our current understanding and build resilient products and production systems. The strategies for resilience could be applied in a manufacturing enterprise either at a component level, assembly level, system level or at the system of systems level. Additionally, with the increasing interconnectivity between the physical and digital threads, the strategies for resilience could be crucial for security and data protection as well.

3.3. *Design for frugality (for resource maximization)*

The above two subsections discussed the ability of biological species to deliver multifunctionality for survival and to demonstrate resilience against potential disruptions or catastrophes. Fighting for and managing available resources forms the third critical aspect of many biological species to ensure their survival in harsh environments. As a part of this combat, effective management and maximization of available resources are paramount. In other words, frugal use of resources is commonly observed in several biological species. 'Frugality' here is defined as the philosophy to minimize the use of available resources while maximizing the productive outputs of a biological species. This concept of frugality has been increasingly used over the past few years, especially in business and sociological contexts to deliver frugal and social innovations [13,22,24,25]. The frugal innovation concept revolves around the reusing, recycling, and repurposing of resources [23,24,183] to deliver effective solutions [143]. The concept of frugal engineering is relatively new and not systematically explored in the literature. Frugal engineering is characterized by at least an order of magnitude reduction in the use of resources (such as time, capital, space, etc.) for invention, innovation, and implementation to address a specific problem [143]. As discussed in the introduction section, the advancement of products demands a techno-socioeconomic perspective. In the context of manufacturing and socially conscious and inclusive designs, one must consider the accessibility and affordability of advanced products in addition to their availability and acceptability. In this context, frugal engineering design methodology was defined as 'a holistic approach of engineering addressing present glocal tech-socioeconomic needs with frugal characteristics, principles, and methods to continuously produce/manufacture frugal innovations' [13] where the term glocal denotes interconnection between local and global events [81]. These aspects of the frugal engineering approach can be commonly traced in many biological species/systems and could offer valuable insight into 'resource-constrained' manufacturing as discussed below.

Biology is inherently designed to be endowed with the ability to sustain the characteristics of survival and growth as it interacts with the environment. Typically, in biological systems:

1. waste is used as raw materials for production;
2. designs are based on the available raw materials accessible to the species in its ecosystem;
3. production technologies are endowed to each member and/or collective of the species colony;
4. processes are tailored to handle and apply that raw material with efficiency, frugality, and effectiveness;
5. production is programmed in the chemical map of the species; and
6. the life cycle of products is based on physical space, air, water, fire/light, and minerals/soil on Earth.

Furthermore, biology, irrespective of the species, is in continuous combat with multiple boundary conditions including access to resources in the given ecosystem, the reach of the biology to access those resources, and the rate at which those resources could be accessed and consumed in harmony and competition with others. In other words, biology is not only effective in striving for the acceptability and availability of resources but also for accessibility and 'affordability' to realize desired designs to achieve the desired functionality(ies) and resilience, while balancing the efficacy, efficiency, and effectiveness at the same time. Hence, biology, the largest production plant biome on earth, is observed to apply the fundamentals of frugal engineering and related designs for equitable production, operation, consumption, and disposal. It relies on four approaches applied towards survival and growth including reusing, repurposing, reconnecting, and reconfiguring.

The frugal engineering approach is manifested holistically through the design of structures, materials, processes, components, systems, and system-of-systems. Especially, it is noteworthy that resilience in biology is manifested in its reaction to the surroundings as the species engage in manufacturing and consuming to survive and thrive within its surroundings. There is a parallel between the reactionary nature of synthetic manufacturing and the reactionary nature of frugal methodology in biology at the respective interfaces.

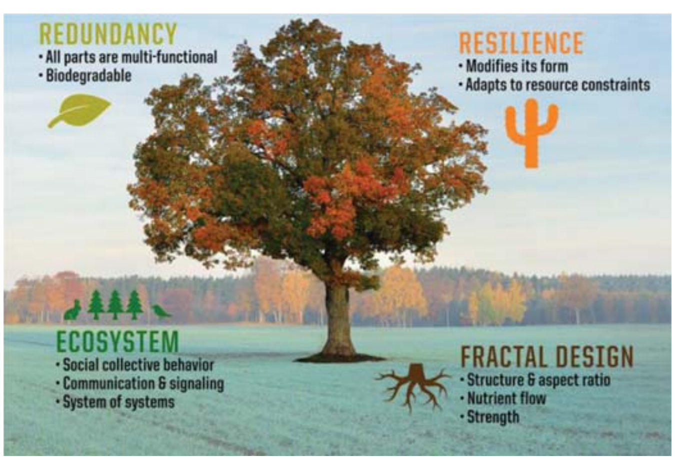

Fig. 12. Example of a tree as a model for frugal resource maximization.

In synthetic manufacturing, this can be observed between humans, global access to raw materials, discretized processes, and heterogeneous physical-digital product interfaces. While in biological species, this could be observed mostly between local raw materials, internalized and symbiotic local processes, and heterogeneous species (as a product) interfaces. For the illustration of this, the authors present an example of a tree (Fig. 12) to discuss the nexus of designs, materials, processes, and systems toward frugality where multifunctionality and resilience play critical complementary roles.

Example-1 (*frugality – fractal design – subsystem*): Branching is observed in trees, both above the ground and underground. One of the primary purposes of tree roots is to scavenge for water and other nutrients in the soil in addition to providing physical support. Plant root architecture is a highly dynamic and complex system, which forms a foraging network, where the roots grow in search of water. The diversity in plant root architectures is due to different local environments. Thus, tree roots form a dynamic branched network also capable of sensing the local environment and actuation [228]. The roots are connected to the tree trunk, which serves as a central component for the transport of nutrients and water. The multiple roots are branched and sub-branched to allow for the larger surface area as well as to enable wider spread underground to seek accessible raw materials. Yet, the branching also allows for scavenging more area while minimizing the overall 3D volume, thus frugally using 'space' as an available resource. The wider spread is essential to ensure a higher probability of effective nutrient/water capture in case of disturbances to underground water patterns and other environmental disruptions that may affect its nutrient supply. Additionally, the network of roots and their intertwining also serves as structural support for trees to cope with terrestrial events such as hurricanes [106]. It should be noted that the division and multiple subdivisions of roots create multiple levels of hierarchy, redundancy, and distributed roles to ensure continued functionality in the wake of disturbances. In contrast, an unbranched structure will be more vulnerable to local disturbances. It is noteworthy that branched roots provide an excellent example of functional integration involving functions such as sensing, load-bearing, and nutrient collection. Interestingly, similar branched architectures can also be observed in other non-living designs such as that of snowflakes and dendritic microstructures where the increased surface area and compact volume is a result of thermodynamic equilibrium.

Example-2 (*frugality – designs for redundancy and biodegradability – components*): Tree leaves, which are components of a central system, are typically tethered to the core system through branches. Leaves offer multiple functions including harvesting the energy for a plant (through photosynthesis), distributing the loads from wind to enhance the tree's survival, superhydrophobicity, sensory network, food for insects as a part of a connected ecosystem, veins in the leaves that allow distribution of food and incoming nutrients, and last but not the least, aesthetics. This multi-functionality, flexibility of different forms along with the ability to biologically disintegrate, is one of the most effective and elegant examples of redundancy in natural systems. Leaves are also an example of redundant solar cells on billions of trees across the planet. The leaves, as they fall and decay, become a part of a large ecosystem demonstrating an outstanding example of a circular economy aligned with the reuse and recycle principles of frugal engineering.

Example-3 (*frugality – harsh environment – designs for addressing resource constraints*): Specific to sustaining life in extreme habitats, plants utilize unique designs (both as a part of surface structures and as a bulk form) to combat environmental challenges. As an example, plants in deserts have modified their form and design for survivability in arid conditions. Plants like the cactus have developed surface structures that enable them to capture fog to extract moisture and at the same time keep predators from eating it or otherwise damaging the plant [105,114] Its surface structures include spines (with pointy tips to initiate capture) in multiple orientations to allow for possible variation in wind patterns and increase the effectiveness of capturing moisture. These spines contain a network of wide and narrow grooves for channeling the water across its length so that it can be collected by the plant at its base through trichomes. This arrangement allows plants to capture, transport, and absorb moisture for survival in the arid climate. Minimization of water loss (as an extremely scarce resource in a desert) while collecting water from moisture depicts frugality in the context of minimizing loss while repurposing other tools for delivering multifunctionality. In another example, carnivorous plants (e.g., Venus flytrap) growing in nutrient-deficient soil rely on unique sensory and actuation mechanisms to lure, trap, and digest insects for food. The sensory hairs inside of the 'trap' sense captured insect movement to activate the shutting of the trap and subsequent digestive sequence [19,97,176,196,245].

Example-4 (*frugality – social collective behavior – ecosystem*): A colony of trees in a forest forms a collective system between themselves to communicate and cohabit together with the animals, birds, bacteria, fungi, and other living organisms, trees and the jungle form a symbiotic ecosystem [12,212,249]. As a representative example, the bacteria in soil are responsible for the decomposition of nutrient molecules to make them conducive to plant growth, the growing plants absorb CO_2 from the air and provide shadows/shelter to the animals (nests), and plant leaves form the fodder to the herbivore animals and the dead animals/leaves decay in the soil to provide nutrients. Collectively, this provides an example of synergy and symbiosis, whereby interaction among various species maximizes the effectiveness of resource utilization and minimizes waste in the form of a circular life cycle.

The methodology of frugal engineering discussed through the above examples provides valuable touch points to the manufacturing of advanced products. This approach could not only be beneficial for resource-constrained manufacturing but also presents a pathway toward socially conscious and inclusive manufacturing [13,145]. From the perspective of a manufacturing enterprise the term 'resource' can be in the form of materials, or in the form of available financial or human capital, or even in the form of available space. The principles of frugal engineering in addition to the utilization of local resources form a crucial pillar for areas such as urban manufacturing, manufacturing in extreme and/or remote environments as well as for the benefit of small and mid-size manufacturers [103,145].

The following section discusses applications of design methodologies and lessons learned from specific species for functions, resilience, and frugality for real-world products.

4. Bio-inspiration of advanced product designs: case studies

Translating biological designs from nature to products is the aim of bio-inspiration design methodologies. Different biological components are classified into seven kingdoms: archaea, bacteria, protozoans, chromista, plantae, fungi, and animals [191]. The animal kingdom (Fig. 13) includes more than 1 million identified and classified species and scientists estimate the presence of at least 8.7 million animal species on Earth [27,158]. The main principles employed to design advanced bio-inspired products are derived from living beings of the animal kingdom. Other kingdoms i.e., the plantae kingdom offer additional bio-inspired solutions in the mechanical field.

	Species number Classified	Estimation
Insects	1000000	8000000
Spiders	102248	600000
Shellfish	85000	200000
Crustaceans	47000	150000
Fishs	31153	40000
Birds	9900	10000
Reptiles	8734	10000
Amphibiens	6515	15000
Mammals	5487	5500
Total	1296037	9030500

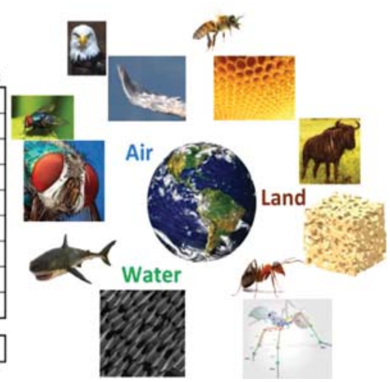

Fig. 13. Animal kingdom Species.

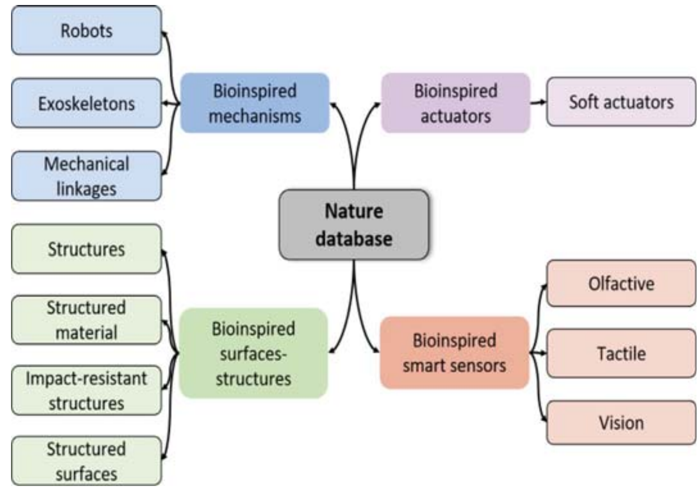

Fig. 14. Sample of advanced and bio-inspired designs.

Numerous biological, chemical, and mechanical functional systems were developed in biology to progress on land, air, and water. As discussed above, these natural systems have been developed through a continuous evolution over millions of years in the Earth's environment under several constraints such as limited natural resources. A set of efficient solutions have developed in biology through natural selection. In this article, only 'successes' are presented, whereas to arrive at these efficient solutions, the process of trial and error of natural evolution has generated very many failures. This has led designers to select only solutions that have 'survived' with a long lifespan. Among the millions of systems created by biology, some developed very advanced mechanical properties. Fig. 14 summarized some examples of these biological systems. Soaring birds (e.g., eagles) have developed specific aerodynamic artifacts on their wings to save energy during flight. Wingtip devices were made by humans to reduce the drag of fixed-wing aircraft. Some insects (e.g., flies) have eyes made up of multiple facets, each acting as an independent light receiver. They contain on average thousands of facets. This structure was mimicked to develop an optical sensor to assist the drive of an unmanned aerial vehicle or other flying systems [75]. To save energy, biology has developed specific textured surfaces to reduce fluid resistance in the water. The shark skin is a good example of these textured surfaces. Their skin is made up of thousands of tiny scales which allows some sharks to reach swimming speeds of around 60 km/h on short distances. A swimsuit designed using the shark skin properties was used at the 2008 Beijing Olympics by Michael Phelps, who won a historic total of eight gold medals. Another example is the exoskeleton of crustaceans or insects that allows supporting high mechanical loads. Ants can hold an object weighing about 1000 times its weight as discussed above [168]. Research works are underway to study wild animals with an endoskeleton. Land mammals developed specific material structures (cortical or trabecular bone). Their multi-scale structure allows for reducing bone weight while maintaining high mechanical performances [9].

From remarkable biological cases from the biological database, advanced product designs have been inspired by mechanical, chemical, optical, and other functions and fields. Due to the vast nature of examples and the overall subject, in this manuscript, the authors focus on and present applications for the mechanical field. In the mechanical field, these designs can be grouped into four categories: biologically inspired mechanisms, surfaces/structures, actuators, and smart sensors (Fig. 14).

4.1. Example category 1: a mimicry degree classification of advanced product designs

Generally, the design process using bio-inspiration allows for answering specific questions: reducing the aerodynamic effects,

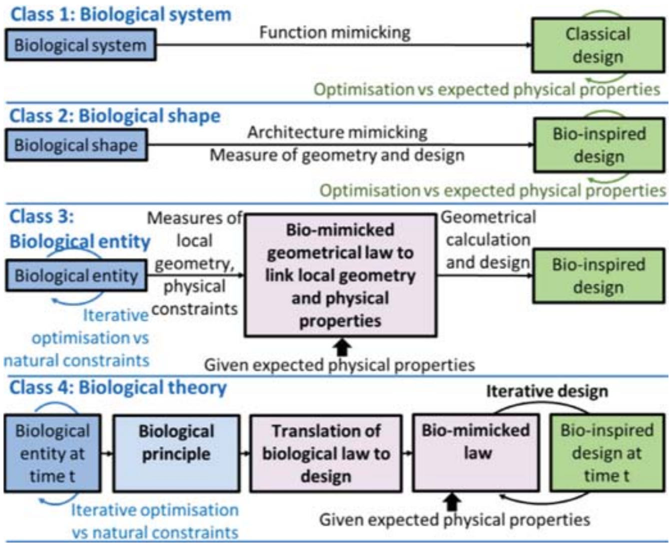

Fig. 15. Mimicry degree classification of advanced product designs.

lightening the product, bringing hydrophobic properties, and improving lifespan. In a biology database, it is rare to find a solution that can be translated, directly, into a mechanical design. In consequence, advanced product design uses partial and local solutions of biological databases. These advanced product designs can be classified according to their degree of mimicry.

Fig. 15 presents 4 classes of mimicry degrees to categorize the advanced product designs. According to ISO TC266 standard [110], both first classes represent the main ways used in bio-inspiration: problem (Class 1) and solution (Class 2) driven. In these advanced product designs, the biological system or shape solution is analyzed and the function or the geometrical architecture is mimicked and adapted to the product design. After, the bio-inspired topology or geometry is optimized using classical design tools to respect the product's physical constraints.

Fig. 16 shows advanced product design examples of classes 1 and 2. The design of the bio-inspired quadruped robot belongs to Class 1. It can perform missions to inspect anomalies in production facilities and access contaminated hazardous areas. This robot becomes more and more popular in the context of I 4.0. This robot allows for overcoming many obstacles like their biological model: stairs, slopes, and more. In this class, mimicry is limited to the global principle of a biological system. Animal kinematics is reproduced using classical mechanical linkages (revolute and sliding prismatic joints). The bio-inspired quadruped robot is powered using classical technologies developed by humans (thermic or electric motors, hydraulic or electric actuators, etc.).

Class 2 is illustrated through an example of advanced sliding bearing design under an off-center load [221]. This bio-inspired design limits contact pressure and reduces wear. To decrease the contact pressure between the shaft and bushing, the factor values of the polynomial contact surfaces (degree 2) were optimized. This shape was mimicked from the elbow of a dorsostable quadruped animal (sheep). The mechanical design of revolute joints is, commonly, made by cylindrical surfaces. In a real mechanism with sliding revolute joints subjected to off-center loads, it has been shown that worn bearings present parabolic wear areas on the shaft and bushing [197]. For cylindrical surfaces, these wear areas evolve during mechanical running-in from a contact line to a parabolic area. Natural evolution considered this issue to increase the contact surface to decrease the contact pressure and, consequently, the wear. Biology uses parabolic shapes to make joints in animal skeletons [194].

The two last classes (3 and 4) are based on a biological process that produces natural solutions. After highlighting a biological law, it is mimicked and applied to the product design. According to ISO TC266 standard [110], both classes require interdisciplinary skills:

1. Biological skills to extract the biological law used in natural entities' evolution to meet the constraint of limited natural resources to which biological beings are subjected.
2. Design skills to translate the previous biological law to bio-mimicked law and design biologically inspired products.

Contrary to the first classes shown in Fig. 15, no optimization is necessary during the product design. This is because the bio-mimicked law includes the properties of the biological optimized entity. In Class 3, the relation between the biological entity and the natural constraints was studied by the biologists to characterize the observed biological entity. This design includes optimized properties (geometrical, chemical, electrical, etc.) developed by biology during evolution. The biological law in Class 4 includes the temporal evolution of the biological entity.

Fig. 17 shows advanced product design examples of classes 3 and 4. These examples are derived from the bone morphogenesis and remodeling principles. Morphogenesis is the process of shape development of a living organism. The morphogenesis foundations were introduced by Turing in 1952. He described this process as a physico-chemical mechanism [230]. This morphogenesis model describes the joint effect of the chemical reactions and the molecular diffusion of reactants. This leads to a spatial variation in the concentrations of chemical species which produces patterns in regularly spaced geometrical structures. This proposition was completed by numerous works [98,171] that highlighted the mechanical basis of the morphogenesis process. A long time before, in 1892, Wolff's model was the first research work about the effects of mechanical loads during bone remodeling [49,250]. The advanced product designs of Class 3 are based on the result (biological entity) of these biological principles. Biological species propose an optimized bone structure regarding applied stress: cortical or trabecular bone (Fig. 18). The bone trabecular topology is linked to the local mechanical stress. Mimicking the trabecular bone scales allometrically in mammal and bird animals, a

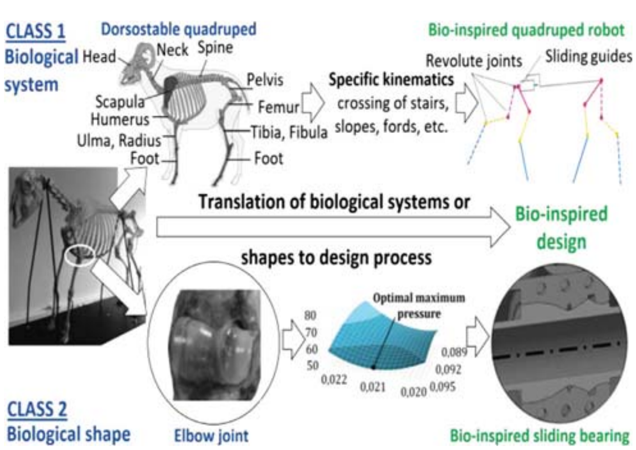

Fig. 16. Advanced product designs of classes 1 and 2 [29, 221].

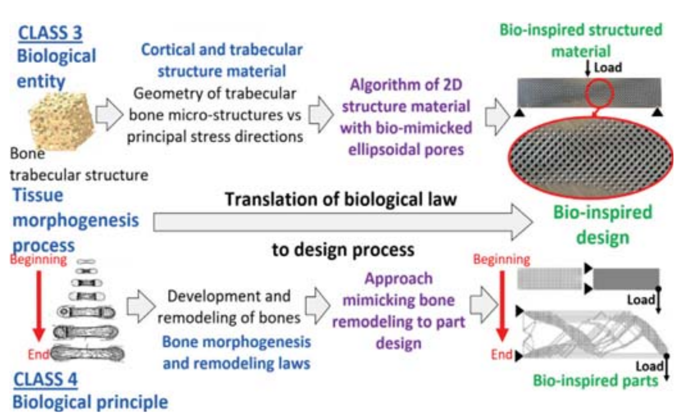

Fig. 17. Advanced product designs of classes 3 and 4 [9, 182].

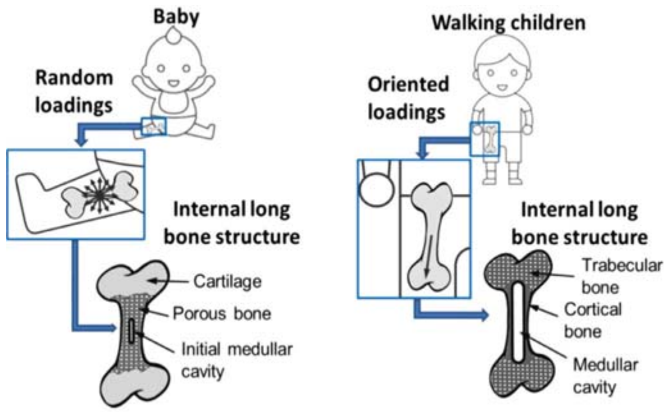

Fig. 18. Effects of mechanical loads during bone remodeling [26].

new bio-inspired workpiece structural optimization approach was proposed [9,26]. In this work, elliptical porosities controlled in shape, size, and orientation were used. This method allows for reducing part weight while maintaining mechanical characteristics. In that paper, experimental tests demonstrated the effectiveness of this bio-inspired method in the static three-point bending case.

A mimicking bone remodeling approach allowing to design of optimized topologies of lattice structures is proposed to illustrate Class 4 [182]. Differential equations of thermal diffusion were used to describe the bone remodeling process. These equations were solved using the thermal model of the finite element method [243]. The resorption or the evolution of cortical bone modifies the bone density that is adapted to the function of strain energy per unit of bone mass. The obtained topology had characteristics like those of topological optimization algorithms with reduced computational costs. Recently, the process of biological joint morphogenesis has been mimicked to improve the mechanical performance of contact surfaces in mechanical links [150]. This biological process is used in biology to create synovial joints. Joint morphogenesis is regulated by tissue adaptations that are related to mechanical and biochemical stimuli. The proliferation of cartilaginous cells allows the development of cartilaginous bone rudiments until the joint takes its final shape. In parallel, endochondral ossification takes place. It begins with the appearance of primary and secondary ossification centers. These structures harden the cartilaginous rudiments until the creation of a bony structure. Mimicking the biological joint morphogenesis, a generative design was proposed to develop contact surfaces [8]. In that work, a computational model of joint morphogenesis existing in the biological literature [182] was adapted to the mechanical field. Using an iterative process, a mechanical simulation predicts the stress field of the parts in contact. From the local stress value, the tissue growth was simulated by a thermal expansion. Thermal and mechanical equations were solved numerically. At each iteration, a new geometry was obtained in a stress-free condition. This bio-inspired algorithm allowed to decrease of the contact pressure in the case of a cylinder/plane unilateral joint of 57%.

The emergence of these advanced product designs is strongly linked to new measuring means (X-ray, optical, etc.) such as tomography (CT scan). These measuring devices allow for characterizing, accurately, at the global scale or local scale the geometric of biological solutions. The geometries observed in biology are typically complex in shape and very far from the manufactured surfaces encountered in classical design (plane, cylinder, cone, etc.). This geometrical complexity requires modeling ability and high computational resources. Computer-aided design and finite element method evolutions have given a solution to model and dimension these bio-inspired products. Likewise, additive manufacturing technology opens new possibilities through its property of decorrelating the cost of the manufactured part from its geometric complexity.

In the next sub-sections, biologically inspired product designs will be discussed.

4.2. Example category 2: biologically inspired mechanism designs

The most well-known designs of bio-inspired mechanisms are bio-inspired robots (Fig. 14). They are designed to evolve into three elements: earth, water, and air. To master quadrupedal gait movement, the animal kingdom was the source of numerous bio-inspired legged robot designs. Unlike rigid legs, quadrupedal legs make it possible to control the pace by simplifying the locomotion dynamic control, to smooth a shock during the race, to run at high speed and, to overcome obstacles, all with low energy consumption [256,264]. The major difficulty encountered in these leg designs was to achieve mechanisms offering flexibility comparable to that of living quadrupeds using standard mechanical components. To solve this problem, pneumatic devices, springs, and deformable parts were used. Recently, mechanisms able to jump were developed [259]. In this case, the mechanical performance is limited by the energy generation and movement control imposed by the jump.

Moving through water was another research area. Fluid mechanics was used to understand the physical properties of fish swim [66,67]. Fish, marine mammals, and other species have led to innovative designs [70,73,151]. The collective behavior of a fish set during swimming can be explained using the laws of fluid mechanics [71]. Fishes have developed specific behavioral rules using the hydrodynamic interaction properties to swim in collective motion. The special in-line pairing of fish needs less energy than the side-by-side configuration to swim at a given swimming speed. It can be used to design advanced strategies to reduce energy consumption in naval or submarine transportation. Based on the water interaction force using the drag coefficient, the run capability on the water was studied to do a biologically inspired quadruped water runner robot [129,175].

New wing geometries and flight techniques based on those of birds, bats, or other animals have been developed [96,222]. In November 2021, the first formation flight of two airliners mimicking geese formation flight was tested. By making them fly one behind the other between Toulouse and Montreal, this formation flight made it possible to reduce six tons of CO_2 emission (gas involved in global warming). This result confirms biology's goal of seeking solutions to reduce energy consumption in a world where it is limited by available resources. Advanced designs of mobile robots can open new uses in search, rescue, and exploration operations in different environments: earth, fluid, or air.

In another field, human enhancement technology refers to technologies to improve the performance of the human body. Bio-inspired exoskeletons were developed and designed to augment human locomotor performance or to help orthopedic rehabilitation [55]. These mechanisms assist locomotion by reducing or helping the user's muscular activity [17,83]. The exoskeleton designs can be classified by the function of design properties (Fig. 19). Around 70% of exoskeletons were designed to assist the lower or upper body and the lower leg of the user (Fig. 19). Only 4% of exoskeletons were studied to help the full body. 84% propose active assistance to the user.

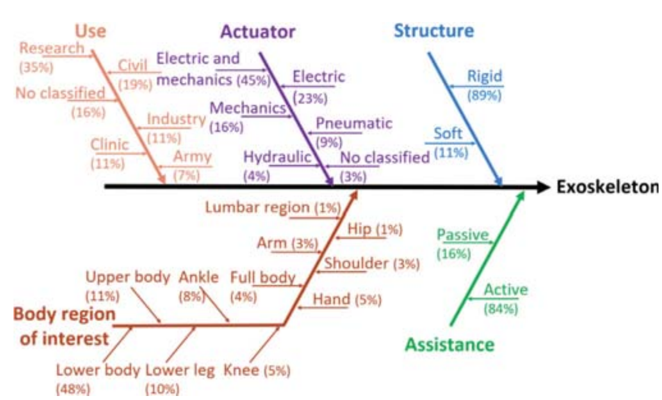

Fig. 19. Exoskeleton design properties [55, 179].

89% of the proposed kinematics is done using rigid equipment. The use of these mechanisms is located at 35% in the research area. The employment of this device is limited to 11% in the industry today. These mechanisms as robots are designed using classical mechanical components (electrical, mechanical, pneumatic, or hydraulic devices). Biological design is more compact and lighter than current products designed using a classical design. New research activities were launched to propose new bio-inspired actuators. The bio-inspired mechanism includes a set of mechanical linkages. The mechanical performance of animal joints was studied in terms of contact pressure and wear. These studies bring to the fore a specific shape to distribute the contact pressure on a greater surface. It reduces the running-in time of bio-inspired mechanical linkages [181,220]. An analysis of animal joints has allowed us to classify these linkages in a set of planar four-bar linkages [161]. Another study highlights some features rarely seen in mechanical design: integrated cam and linkage mechanisms, nonplanar four-bar mechanisms, resonant hinges, and highly redundant actuators [33]. The bio-inspired innovative design of articulation concepts was proposed by ESA [232,237].

To summarize the key points of this subsection, bio-inspired mechanisms have been designed to move on land, sea, and air. The mimicry of the flexibility and the motion resolution of living beings in advanced mechanisms are open research questions. To obtain more efficient exoskeletons with better comfort for the user, research actions could relate to an interdisciplinary consideration of human anatomy, physiology, biochemistry, biophysics, and biomechanics. The social behavior of wild animals regarding their displacement strategies could be mimicked to reduce energy losses in transport applications.

4.3. Example category 3: biologically inspired surface and material structure designs

Biology uses surface or material multi-scale topologies to answer challenges imposed by the life and survival of different species living on Earth. The design of advanced surfaces or structured materials finds its inspiration in the database made available to us through a wide variety of biological species. Bio-inspired surfaces have been a popular study field. The main sources of these designs were extracted from animal or plantae kingdoms. Numerous geometrical principles were mimicked to improve adhesion or frictional anisotropy, super-hydrophobicity or hydrophilicity, antireflection, and other optical properties [137,148]. The natural surfaces' micro-nanostructures make it possible to generate many of these properties [208,253,263]. These multi-scale geometries facilitate the interaction between the object's surface with water, light, and earth with efficiency. Fig. 20 summarizes a set of animals or plants that propose solutions to surface technical problems. Moreover, the flexible natural armors from animals (fish scales and osteoderms) were the source for the design of advanced bio-inspired flexible protections [63,152].

The research about bio-inspired material design is, mainly, based on the use of biological material and structures derived from plantae

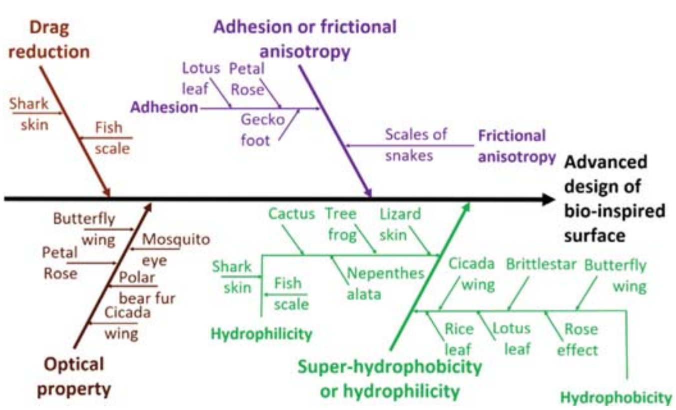

Fig. 20. Sources of bio-inspired surface designs [137, 148].

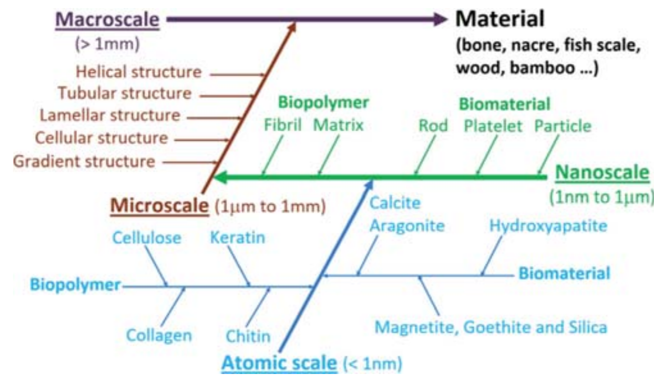

Fig. 21. Multi-scale and hierarchical components of biomaterials [80, 108, 165].

or animal kingdoms (Fig. 21). At a large scale, their geometry can allow the designing of bio-inspired architectures in civil engineering, [156]. In the same way, the structure design of large machine-tools was mimicked plant ramifications' growth principle [132].

Studies were done about the plantae material microstructure (wood, palm, and bamboo) [80] and the multi-scale/hierarchical assemblies in biological materials [108,165]. These material structures give some interesting properties: light in weight, strong strength, and hardness. These optimized values were achieved through natural evolution over millions of years. These multi-scale and hierarchical structures are used to allow energy dissipation and absorb the strain energy generated during mechanical or thermal loading. Some specific material structures have the property to deflect and stop the crack propagation in the material. Based on this knowledge, advanced artificial material designs were developed mimicking the multi-scale structure developed in biology. The constraint limiting the design of these artificial multi-scale structures is the difficulty of their manufacture. Using freeze casting [90] and additive manufacturing [123], bio-inspired composite materials mimicking the nacre or bone structures were designed. Other technologies are available to design and manufacture, down to below micron scales, these multi-scale structures [108,165]. Mimicking the long bones' macroscale, new bio-inspired algorithms were implemented to lighten the mechanical parts while safeguarding their mechanical properties [9]. These new bio-inspired material designs have accelerated the translation of man-made materials (usually steel and alloys) to structured materials at multiple scales (macroscale, microscale, nanoscale, and atomic scale).

The future research challenge on bio-inspired surfaces is to propose design methodologies able to integrate specific geometries on the surface allowing the improvement of drag, adhesion, anisotropic friction, optical properties, super-hydrophobicity, or hydrophilicity depending on the product functional expectations. In the long term, bio-inspired models could make it possible to automatically design functional surfaces according to the wanted mechanical or optical properties. In the same way, advances could be made in the design of materials by relying on the multi-scale and hierarchical structures present in natural materials. Advances are expected in the proposal of materials able to present contradictory mechanical properties (light and resistant; light and resilient to deterioration) and able to repair themselves.

4.4. Example category 4: biologically inspired soft actuator designs

Conventional robots are designed using rigid components, and they are driven by electric, hydraulic, or pneumatic actuators. These robot designs resulted in large and heavy design solutions. In these solutions, separate modular systems were used. For each function, a specific component was employed: actuation, sensing, and control. In consequence, bio-inspired robots need more soft actuators for mimicking natural movements. The new challenge for designers is to mimic the natural solution compactness as the muscle multi-scale structure goes from the sarcomere (micro-scale) to the whole muscle

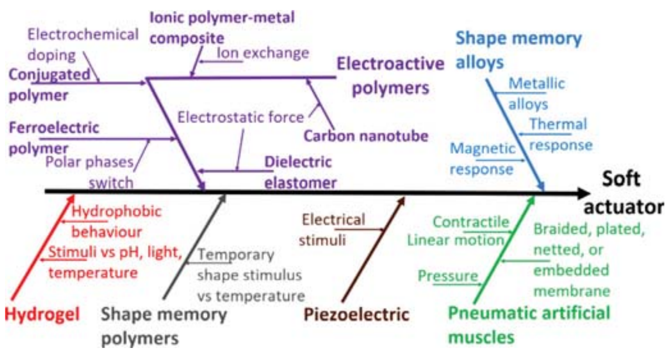

Fig. 22. Artificial actuator technologies [109, 133].

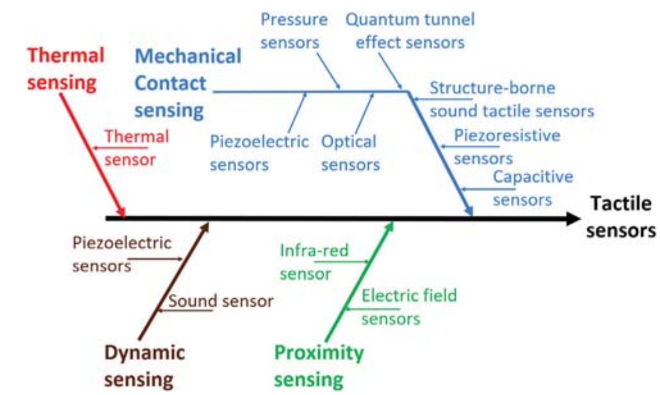

Fig. 23. Principles to artificial tactile sensor design [115, 211].

(macro-scale). These new solutions can integrate perception and action functions in the actuator. To answer this challenge, research works have proposed artificial solutions to design advanced bio-inspired soft actuators (Fig. 22). Fig. 22 shows the technologies used to reproduce the behavior of muscle tissue and plant fibers into a bio-inspired soft actuator. Studies were done to characterize the muscle's mechanical behavior such as negative equilibrium stiffness and different behaviors when the load is controlled by force and displacement [38]. The skeletal muscle multi-scale topology (sarcomere, myofibril, myofiber, and muscle) [119,229] and its control are complicated to mimic and this aspect is further highlighted in Section 6 as a part of cellular agriculture example to manufacture edible meat product. Vascular artificial muscle design was proposed using soft actuators [95,186].

Future challenges for designing advanced actuators require considering the multi-scale aspect of actuators present in biology such as striated muscles and actuators present in the leaves or stems of plants. Today, no artificial actuator can satisfy all the actuation requirements (low mass, high resilience to perturbation, responsiveness, adaptability, etc.) of the natural muscle [133]. In actual design, the limiting factors are low output force, delayed response, and short lifespan (delamination between rigid and soft components).

4.5. Example category 5: biologically inspired smart sensor designs

The biological database offers many sensor principles to investigate the environment (perception task) and control the motion (walking, running, flying, etc.) of living beings. Research work was carried out in three specific areas of detection: vision, tactile and olfactory.

Two approaches are mainly used in artificial vision: the capture of image cameras (photoreceptors inspired by the eye) [109] and light flux sensors. The first approach requires merging the images taken one after the other to extract the position gradient. This needs a lot of electronic hardware and computation to extract information about a dynamic environment. On the contrary, the stimulation flow on the animal eye retina is continuous and sufficient to localize [79]. This way gives a frugal design of a bio-inspired vision sensor. A bio-inspired and minimalistic compound eye containing only three photoreceptors and a lens was designed during the framework of the European project CurvACE [75]. White light given by the sun comprises a set of wavelengths that can be characterized by their polarization angle and degree of linear polarization. The Earth's atmosphere polarizes part of the sunlight in the main orientation such as the role of the linear polarizer. Animals use this property for their navigation on Earth. Based on this physical phenomenon, biomimetic and frugal celestial compasses have been proposed [62,117]. These designs are lightweight and resistant to various environmental conditions in opposition to Global Positioning Systems (GPS), inertial measurement units (gyro), or magnetometers.

Touch perception is another way to investigate the environment or manipulate an object using the contact or a light touch between the skin and a surface (temperature, pressure, surface, or object recognition). The skin includes different tactile receptors: thermoreceptors (thermal sensing), mechanoreceptors (pressure or deformation sensing), nociceptors (pain and irritation sensing), and proprioceptors (detecting motion and body position through a stimulus i.e., touch). The criteria to design bio-inspired tactile sensors are spatial resolution, sensitivity, frequency response, hysteresis effect, and surface mechanical compliance [115,211]. Fig. 23 summarizes the technologies used to mimic the skin receptors. The tactile perception mastery lies in the interpretation of numerous and simultaneous data provided by all sensors. Olfactive sensing is another field of bio-inspired sensor design. Bacteria, protozoans, fungi, plants, and animal kingdoms have developed a sense of smell to differentiate food, route direction, potential hazard, partner, and predator [155]. The odor characterization is the fit between a molecular volume of odorants and an olfactory neural response [32]. Each odorant is coded by a unique combinatorial response and identified from an olfactory receptors' library. Each animal has developed a complex system of specific receptors (olfactory sensory neurons, chemoreceptors, and odor-specific receptor proteins) [246]. The advanced design of bio-inspired olfactive sensors was proposed. Two fields were addressed: sensors [45,258] devices, and data treatment [104]. The main difficulty is detecting and recognizing the large combinations of odorants present in biological examples. The sensing effects used in olfactive bio-inspired sensors are:

1. electrical resistance change in response to nearby chemical environment (chemiresistors);
2. polymer behavior modification to detect single-stranded DNA sequences, and metal ions using atomic force microscopic principle (polymer-coated and micro and nano-cantilever arrays);
3. surface potential change induced by the binding of molecules (biosensor field-effect transistor), vibration detection of molecular adsorbates on metal oxides (inelastic electron tunneling spectroscopy); and
4. optical properties evolution of odorant particles (fiber Optic Array Biosensors and mesoporous Bragg layers).

Research on bio-inspired sensors is growing in the specific fields of vision, olfactory and tactile recognition. The sensor principles used by animals and highlighted by bio-inspiration, or biomimicry are generally simple and frugal. However, the current designs of bio-inspired sensors are complex. In many cases, the design of these advanced sensors is an assembly of conventional technologies that only mimics biological functionality, but not its principle. Hence, it is very difficult to have an overall view of the research carried out in this sector. The future challenge in this area of research is to better understand the fundamental principle of biological sensors. This knowledge will make it possible to design frugal bio-inspired sensors such as the CurvACE vision sensor or the polarized celestial compass. For that, an interdisciplinary approach is necessary to understand and recreate the active principle used by animals.

To conclude Section 4, biological database has allowed designing advanced products using bio-inspiration. Additionally, most of these product designs make use of apparent solutions offered by living objects or things in biology. Generally, the actual technology (products of electronic or mechanical designs) is used to reproduce natural objects or living things. These products can be classified into the first two classes (Class 1 and 2) defined above.

Future challenges in advanced product design will be to consider the properties of living material (i.e., material regeneration, hierarchical and multi-scale structures). The biologicalisation of product design needs interdisciplinary skills (anthropology, biology, chemistry, mechanics, electronics, etc.). The understanding or consideration of biological principles used by biology to design advanced products is recent due to their complexity. One of the first bridges between scientific thematizes to understand biology's behavior in living was Turing's work on morphogenesis linking chemistry and biology. Turing's work opens perspectives toward the design of advanced products which might inherit the advantages of biological structures (frugal in energy, resilient, multi-scale, and others). This way made it possible to begin the design of advanced products including the advantages of products made by biology (frugal in energy, resilient, multi-scale, and other). They can be ranked in classes 3 and 4 of the classification proposed previously. Recently a definition and metric of resilience were proposed for the design of bio-inspired actuators [180]. This metric, which allows quantifying the resilience, was calculated for four actuator types: hydraulic cylinder, McKibben bio-inspired muscle, pulvinus, and biceps muscle. A correlation between the multi-scale properties of the structure and its resilience has been highlighted in this work. The design of these products will make it possible to give the properties acquired during the natural evolution of objects or living beings such as, for example, the resilience property to change applied constraints.

5. Summary and conclusions

In summary, this manuscript analyzed the biologicalisation concept partly (bio-inspired and biomimetic) through the lens of the production design discipline. The discussions across the manuscript present design principles, practical approaches, and their implementation strategy through three pillars. Pillar 1 analyzed bio-inspiration in the framework of a biological encoder and biological decoder. Biology is presented in the framework of the natural environment, biological system, and axis for a time as a dynamic ecosystem. This framework, once decoded, can be implemented in the framework of synthetic manufacturing with three axes of advanced products, market competition, and axis of time. The authors further discuss the role of biology in the context of product complexity, constraints, cognition, collaboration, integration, adoption, and evolution. The manuscript further discussed the values and opportunities of bio-inspired product designs through three classes and finally concludes with the design value creation model for bio-inspiration. Pillar 2 presents biological designs for delivering multifunctionality, resilience, and frugal engineering in a unified platform. This pillar extracts various design structures and strategies biology has abundantly implanted across various species and provides critical examples and their analysis. The examples of these design strategies span across the length scale boundaries and are observed across animals, plants, microbes, and humans. These strategies include hierarchical integration, redundancy, branched fractal structures, and the ability to frugally use minimum resources in collective ecosystems. The third pillar advances the outcomes of the first two pillars through extensive case studies. This section classifies advanced product designs through biomimicry degree classification. This section uses specific examples of biological designs and their correlations to a range of products such as quadruped robots, sliding bearings, and elbow joints. This section also analyzed biological designs not only for systems and components but also for the materials through the effective use of fishbone diagrams. This section analyzed the design properties of key structures including exoskeletons, bio-inspired surfaces, advanced materials, soft actuators, and tactile sensors. In conclusion, this keynote paper presents a systematic analysis of learning designs from biology; the methodology to extract product-critical information that is coded in biology; the implementation of this knowledge to engineer a product with multifunctionality, resilience, and frugality; and finally, present that in the form of schematic diagrams for retaining the knowledge systematically for future implementation.

One of the main intents of establishing this biological design framework is to uncover new ways to implement advanced product design methodologies. These advancements are becoming far more time-sensitive as the world is experiencing hyper-complex problems due to trends and drivers in industrialized and industrializing nations.

6. Future directions

During advancements of Industry 4.0 (I 4.0) and digital integrated physical smartness, we experienced major global trends including the growing population and the size of the consumer middle class, increasing average human life expectancy, climate challenges, increasing frequency of pandemics, fast depleting natural resources, rate of urbanization, nutrition insecurity, growing activities of the human race in extraterrestrial environments, and potential calamities, and many more [89,121,131,149,167,200,214,251,254]. Despite the smartness offered by the combination of digital and physical advanced products and services, the world is experiencing growing inequity in basic human needs such as nutritious food, affordable housing, education, clothing, health care, and more [143]. These inequities, which are at the point of need (PoN) are distributed. During the same period, we are also seeing transformative manufacturing aspirations and advancements for manufacturing alternative protein food (e.g., meat) using biomanufacturing to address food security; servicing, assembly, and manufacturing in space (e.g., bio-inspired neuromorphic semiconductor and micro/nanodevices for AI) for commerce, security, exploration; and precision medicine for equitable health care and more. These and related global trends, severe inequities in basic human needs, and ambitious manufacturing advancements are major drivers to inquire and inspire the production community to 'rethink smartness' for not only productivity, producibility, and profitability as evaluation metrics but also availability, acceptability, accessibility, and affordability of socially conscious and inclusive equitable products and services at the point of need, including for basic human needs [65,107,139,159,160,255]. We imagine a inclusive design and manufacturing platforms that not only provides productivity but also products' multifunctionality, resilience under resource constraints, and frugal engineering methodology to provide equity at the PoN [13]. We learned about this design platform in biology and have uncovered it in this paper. Biological designs and enabling materials and manufacturing processes are typically converged (available, applied, and executed) at the PoN. Learned from the study in this and prior manuscripts authors propose Convergent Manufacturing [39], a different complementary approach for the future of manufacturing.

Convergent Manufacturing (Fig. 24) is the science and engineering of converging or integrating heterogeneous materials and hybrid processes in one platform. The materials are heterogeneous in their chemistries and length scales (nano-to-macro) of engineering, alike several biological examples discussed in this paper. The hybrid processes include methods to add, subtract and phase transform these heterogeneous materials. The convergence in one platform allows the reduction in discretization based on materials and their manufacturing processes. This convergence in one platform brings an opportunity for offering wide choices of designs and production close to the PoN and reduces latencies in delivering services and increasing efficiency and opportunity for providing equity. Biology in nature has mastered this art of convergent manufacturing for maximizing available local resource utilization under server boundary conditions at the point of need and delivering multifunctionality and resilience, frugally to biological species. The biological designs, and synergistic materials and processes, allow such a methodology. Fig. 24 shows a pyramid founded on the above-listed example transformative applications, where a higher level of functional customization and extremely stringent requirements including on resources demand convergence of heterogeneous materials and processes at the PoN

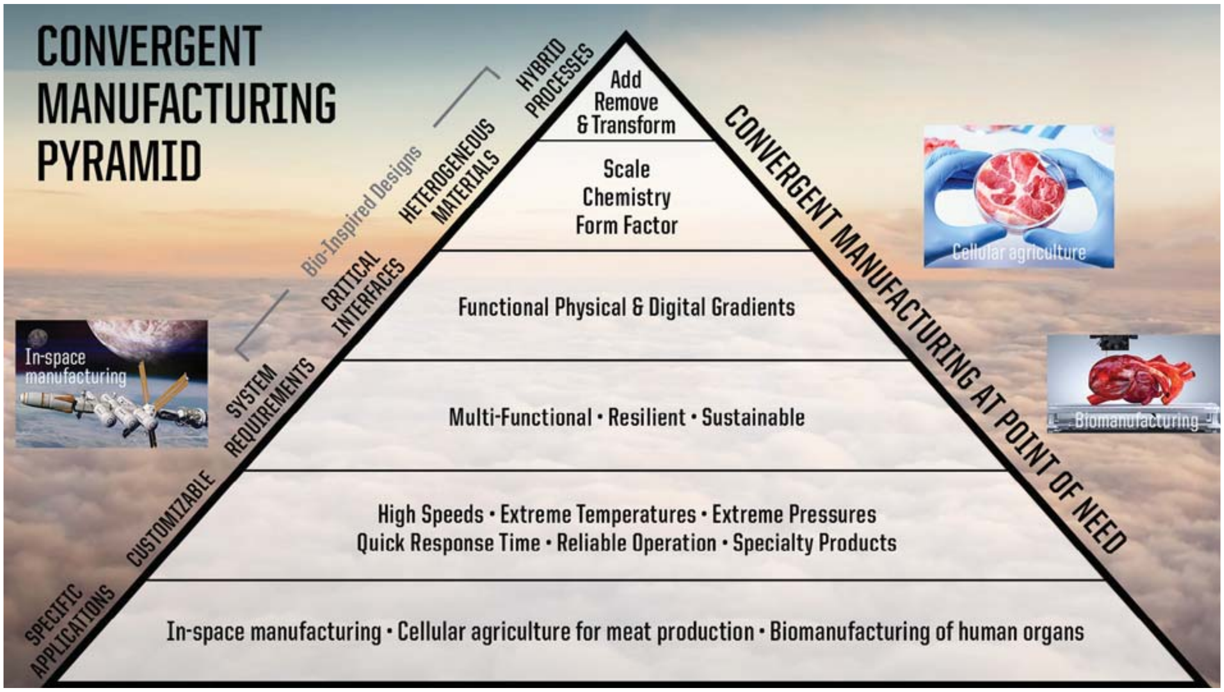

Fig. 24. Convergence in manufacturing for looking beyond Industry 4.0 for the next generation of example applications.

where customers are for mass-scale customization. Following is an example case of cellular agriculture to illustrate salient points of convergent manufacturing.

Example Case Study *(Convergent manufacturing for cellular agriculture)*

Cellular agriculture is a biomanufactured cellular construct mimicking or inspired by the design construct of naturally occurring protein meat originating from animals. It is projected as an effective way to address food security at the PoN by urban production and reduce climate impact caused by emissions involved in growing livestock such as cattle. Cellular agriculture has emerged, over the past decade, as a revolutionary production method disrupting a way of traditionally making meat food from livestock by top-down processes for over a thousand years [14]. Cellular agriculture is an alternative way to produce edible meat products from novel methods of biomanufacturing. These methods include harvesting novel cell lines, scaffolds, growth media, bioreactors and incubators, modular manufacturing methods, and more. Muscle fiber structure for food consumption is seen in a slice of meat (Fig. 25), like a steak or chicken breast, demonstrating the hierarchical distribution [85] with the precision of various types of cells and their combinatorial constructs in length scales, type of cells embedded with blood vessels, assembly of heterogeneous fibers, and expression of cells as they go through different phases of production from slaughtering to cooking exposed to various time, temperature, and phase transformations. This is one of the examples of heterogeneous materials and their precision placement in one production construct. In nature, biology is driven traditionally by slow bottom-up manufacturing methods including trillions of various types of cells designed in an organized manner to deliver synchronized functionalities as the purpose is for animals to 'live'. On the contrary, the aim for a piece of meat to be consumed is for providing nutrition, taste, and mouthfeel, and more apt to a consumer at an affordable price like a few cents for chicken nuggets. To achieve these stringent demands, rapid and novel biomanufacturing processes [201] are emerging such as fast growth of cells by 'overcoming' biological limitations, new design of meat and their scaffold constructs, and hybrid manufacturing processes integrated with assembly to make hierarchical fiber structures that are shown in Fig. 25. Additionally, advancements in the areas of sensors, in-situ process monitoring, characterization and evaluation methods for assessing the meat quality (taste, texture, mouthfeel, and safety), must also be developed for scaled up production and reducing the product costs. It is apparent that a combination of heterogeneous materials and their bio-mimetic or bio-inspired designs constructs, combined with combinatorial hybrid biomanufacturing processes and in a manufacturing facility accessible to consumers to address nutrition equity illustrates an emerging example of convergent manufacturing, alike biology in nature. In summary, similar convergence in manufacturing is observed in other examples, as illustrated in Fig. 24. The findings from research in this paper open the following scientific and engineering inquiries and opportunities for future work:

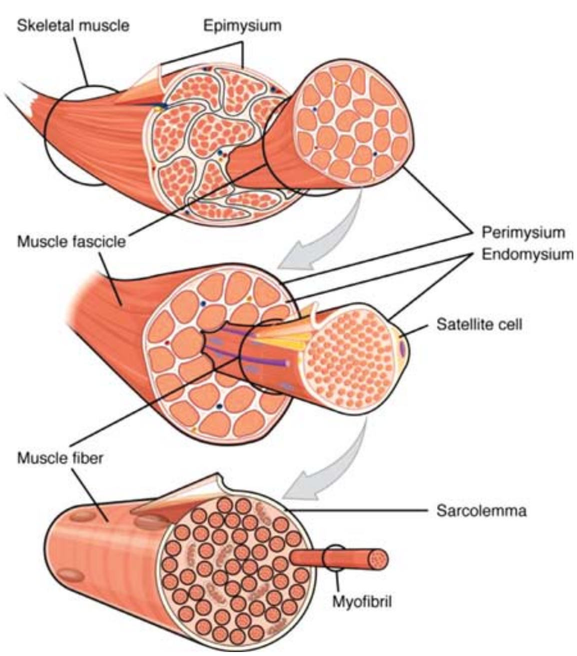

Fig. 25. Hierarchical structure of a muscle fiber. Image reproduced from [85] under creative commons license.

1. What is the integrated design model for biology across length scales, signals, heterogeneous parts, and other boundaries? How this model aligns and differentiates from the current synthetic design model?
2. What is the synergistic role of mechanical, electrical, chemical, neural, optical, and other components in the design framework for the orchestrated response of a biological system?
3. How is 'intelligence' integrated into the biological design model? Could it be imagined the 'hard AI' of biology?
4. What educational framework is desired to integrate biology-driven learning in teaching the next generation of the manufacturing workforce?
5. What is the role of the thesis of convergence in advancing the frontiers of manufacturing, beyond Industry 4.0?
6. What new type of 'smartness' in manufacturing we can imagine bridging the inequity gaps in basic human needs across the globe?
7. What lessons one can learn from the diversity in biology and manufacturing models to advance diversity in the manufacturing workforce?

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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