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Supporting Multifunctional Bio-Inspired Design Concept Generation through Case-Based Expandable Domain Integrated Design (xDID) Model

Pavan Tejaswi Velivela and Yaoyao Fiona Zhao *

Department of Mechanical Engineering, McGill University, Montréal, QC H3A 0G4, Canada; pavan.velivela@mail.mcgill.ca
* Correspondence: yaoyao.zhao@mcgill.ca

Abstract: Combining different features inspired by biological systems is necessary to obtain uncommon and unique multifunctional biologically inspired conceptual designs. The Expandable Domain Integrated Design (xDID) model is proposed to facilitate the multifunctional concept generation process. The xDID model extends the previously defined Domain Integrated Design (DID) method. The xDID model classifies biological features by their feature characteristics taken from various case-based bio-inspired design examples into their respective geometric designations called domains. The classified biological features are mapped to the respective plant and animal tissues from which they originate. Furthermore, the paper proposes a representation of the functions exhibited by the biological features at the embodiment level as a combination of the integrated structure (multiscale) and the structural strategy associated with the integrated structure. The xDID model is validated using three multifunctional bio-inspired design case studies at the end of the paper.

Keywords: bio-inspired design; conceptual design; bio-inspired innovation; multifunctional bio-inspired design; bio-inspired technology

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1. Introduction

Numerous studies conducted in the past propelled the idea that biology is a source of inspiration for solving design problems. Nature's strategies have inspired scientists and engineers to develop innovative solutions to complex engineering problems; for example, Namib Desert beetles inspired the development of structures for water absorption in water-scarce environments [1], Nacre inspired structures for compression resistance [2], etc. Bio-inspired design (BID) is an approach that uses analogies to biological systems to develop innovative solutions to difficult or complex engineering problems [3,4]. BID can create opportunities for radical technological innovation [5] and sustainability [6]. However, it is essential to understand why biological inspiration is a source for generating multifunctional and multiscale products. Biological systems or organisms are multifunctional, meaning they perform various tasks simultaneously for survival [7]. Studies by Ren and Liang [8,9] and Du Plessis et al. [10] reported that organisms function by using minimum energy and minimum material usage, thus reducing the number of parts and increasing the efficiency of performing a particular task. In addition, biological materials are multifunctional, offering solutions for many complex engineering problems [11]. Han et al. [12] stated that billions of years of evolution have enabled living organisms to evolve into an intricate combination of different elements. Living organisms have developed strategies and functions for survival in their environments. San Ha and Lu [2] reported that many structures found in nature (animals and plants) possess excellent energy absorption functions compared to conventional structures. Furthermore, Zhang et al. [13] identified that natural selection is responsible for living organisms developing optimized systems. For example, lotus-leaf microstructures are used in many applications, such as self-cleaning and drag reduction in fluid flow. Bhate et al. [14] reported that natural cellular structures could be applied in various engineering applications such as weight reduction, strain isolation, vibration control, heat exchangers, heat isolation, acoustic liners, catalyst carriers, packaging buoyancy, cell growth, etc. However, it is imperative to understand the principles and mechanisms of the functions exhibited by biological systems to emulate their strategies and to develop efficient products.

To utilize nature's efficient strategies to solve highly complex engineering problems, frameworks, methods, and tools were developed to emulate nature's design principles. Most of the resulting methods and tools assist in emulating only one function. Only a few methods help in emulating multiple functions. Methods for multifunctional BID include BioGEN [15], product architecture-based function-sharing [16], BioTRIZ [17], function-means [18], multi-biological effects (MBE) [19], multi-bionics [8], the trimming method [20], system-of-systems BID [21], and compound analogical design [22]. However, the newly developed domain-integrated design (DID) method is distinct and offers much more detailed classification, mapping, and representation of the relevant biological systems for a multifunctional design problem. The distinctions between the DID method and existing multifunctional BID methods are discussed in detail in [23]. The critical difference between the existing multifunctional bio-inspired design methods and DID is the classification of biological features by their characteristics into geometric designations called domains and mapping them to the respective animal and plant tissues from which they originate. The domains are surfaces, cellular structures, cross-sections, and shapes. Integrating the biological features of different domains results in achieving uncommon and unique multifunctional and multiscale design concepts. Biological features refer to the morphological and anatomical features observed in the plant and animal kingdoms. The biological feature characteristic represents the appearance, apparent form, or physical traits of the feature; for example, the body/skin texture, hard outer composite covers such as outer composite plates, outer composite tiles, outer composite shells, and cellular structures, etc., represent biological feature characteristics. Domains represent different biological features performing various functions, mapped to their tissues with a common geometric designation. The biological features from these classified domains are combined to generate multifunctional and multiscale conceptual designs [23]. The DID method is validated by the design of painless sutures inspired by the combination of a kingfisher's beak from the cross-section domain and the barbs on porcupine quills from the surface domain [24].

The previously proposed DID method reduces the gap between technology and biology by uniquely classifying around 50 biological features (currently) to their respective geometric designations and mapping the classified biological features to the tissues from which they originate. Furthermore, the unique classification and mapping system enabled the creation of a knowledge database and the extraction of parameters for relevant biological feature selection under convergent evolution. Convergent evolution is where distinct biological systems have biological features that exhibit similar functionalities. Moreover, the method's combination of different features enables the combination of uncommon or contrasting functions that are not addressed by existing multifunctional BID methods.

This paper presents the expandable DID model (xDID), which is an extension of the DID method, and explains how this model supports multifunctional design concept generation. In addition, specifically in the xDID model, the function is defined as a combination of integrated structure (multiscale) and its associated structural strategy. This paper is organized as follows. Section 2 elaborates on the case-based classification framework and presents details on the cellular biology of plant and animal kingdoms, mapping of biological features, and defining domains. Section 3 presents function in biological systems and introduces the meta-level embodiment function as a combination of integrated structures (multiscale) and its associated structural strategy. Section 4 presents the xDID model and its application by using multifunctional bio-inspired conceptual case studies, followed by conclusions in Section 5.

2. Case-Based Classification Framework, Mapping, and Domain Definitions

Classifying and mapping biological features from the gathered examples by their characteristics is a sequential process. As shown in Figure 1, the first step is classifying biological features by their characteristics into their respective domains (geometric designations). The second step is mapping the biological features to their respective plant and animal tissues. The biological features here are the morphological and anatomical features observed in the animal and plant kingdoms. The biological feature characteristic represents the feature's appearance, apparent form, or physical traits. For example, the biological feature characteristic of a sharkskin riblet is the body/skin texture. Likewise, a shell is a biological feature characteristic of a mollusk's protective surface.

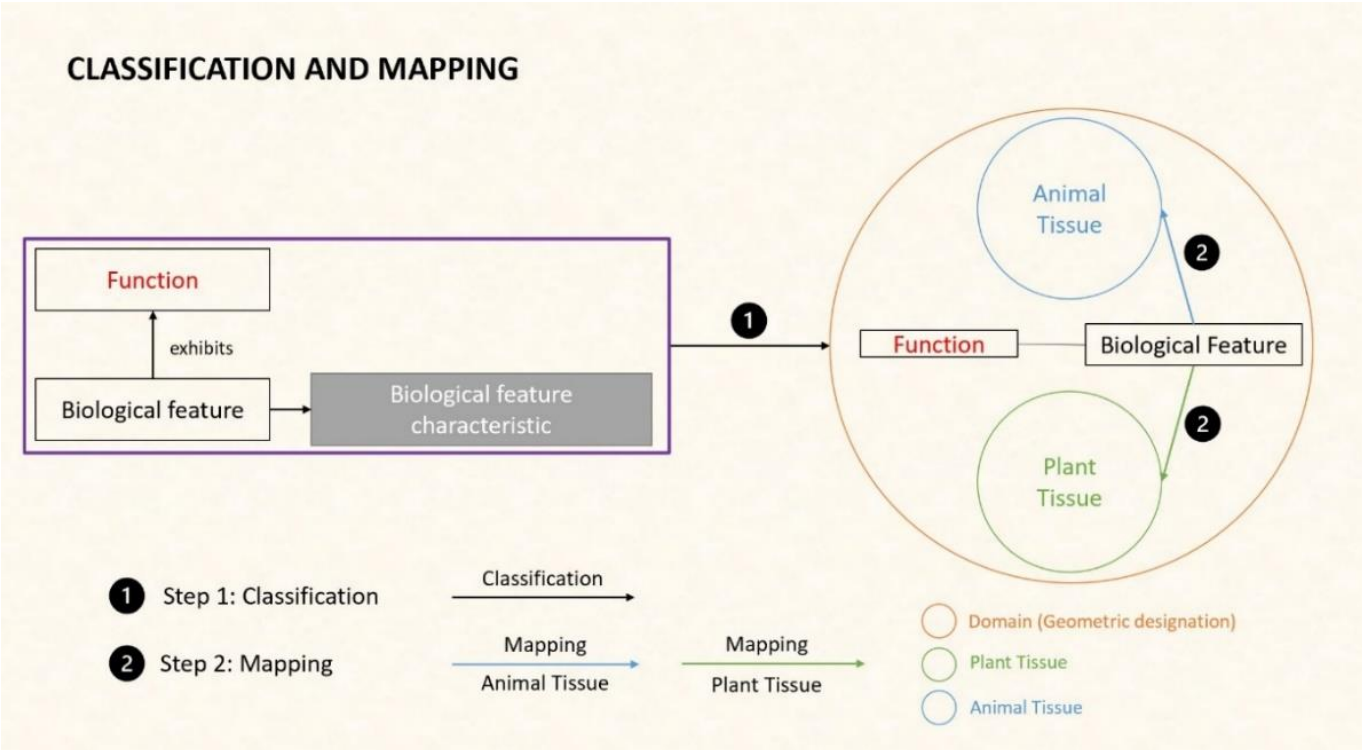

Figure 1. Classification and mapping schematic of xDID.

The biological features and the functions they perform are taken from analyzing around 50 bio-inspired design case studies from the literature. The classification of the biological features by their biological feature characteristics is elaborated using the classification framework shown in Figure 2. The following presents the technique used to classify the biological features into their respective domains.

- Biological features exhibiting a function with a feature characteristic (such as body/skin textures, scales, body coats for example, wool, hair, scales, etc.) and elements that include the hard outer composite covers (such as outer composite shells, outer composite plates, and outer composite tiles) are classified to the surface domain. For example, the superhydrophobic property of the micro/nano projections on the lotus leaf [13], and the wear-resistant function of the scales of a burrowing pangolin [25].
- Biological features exhibiting functions that have features characteristic of porous prismatic and foam structures arranged in various tessellated patterns, namely periodic, stochastic, and hierarchical, with feature characteristics such as periodic tessellations with unary, binary, ternary, or quaternary connections, stochastic tessellations with Poisson distribution, Voronoi, or crystal growth patterns, and finally, hierarchical tessellation with branching, nested, or overlaid connections [14], are classified as

belonging to the cellular-structure domain. For example, the absorbing function of the hierarchical tessellations of a beetle's elytra forewing [26].

- If the function is achieved by biological features with characteristics such as the overall shape (full body contour) of a biological system, or the shape of a part of the biological system (contour of a part of the body), it is classified as belonging to the shape domain. For example, the drag-reducing function produced by the overall shape of the boxfish's body [27].
- If the function is achieved by biological features with characteristics such as the cross-section of the biological system or cross-section of a part of the biological system, it is classified as belonging to the cross-section domain. For example, the ability to reduce the rupture function of the rotational parabolic cross-section of the kingfisher's beak [24,28]

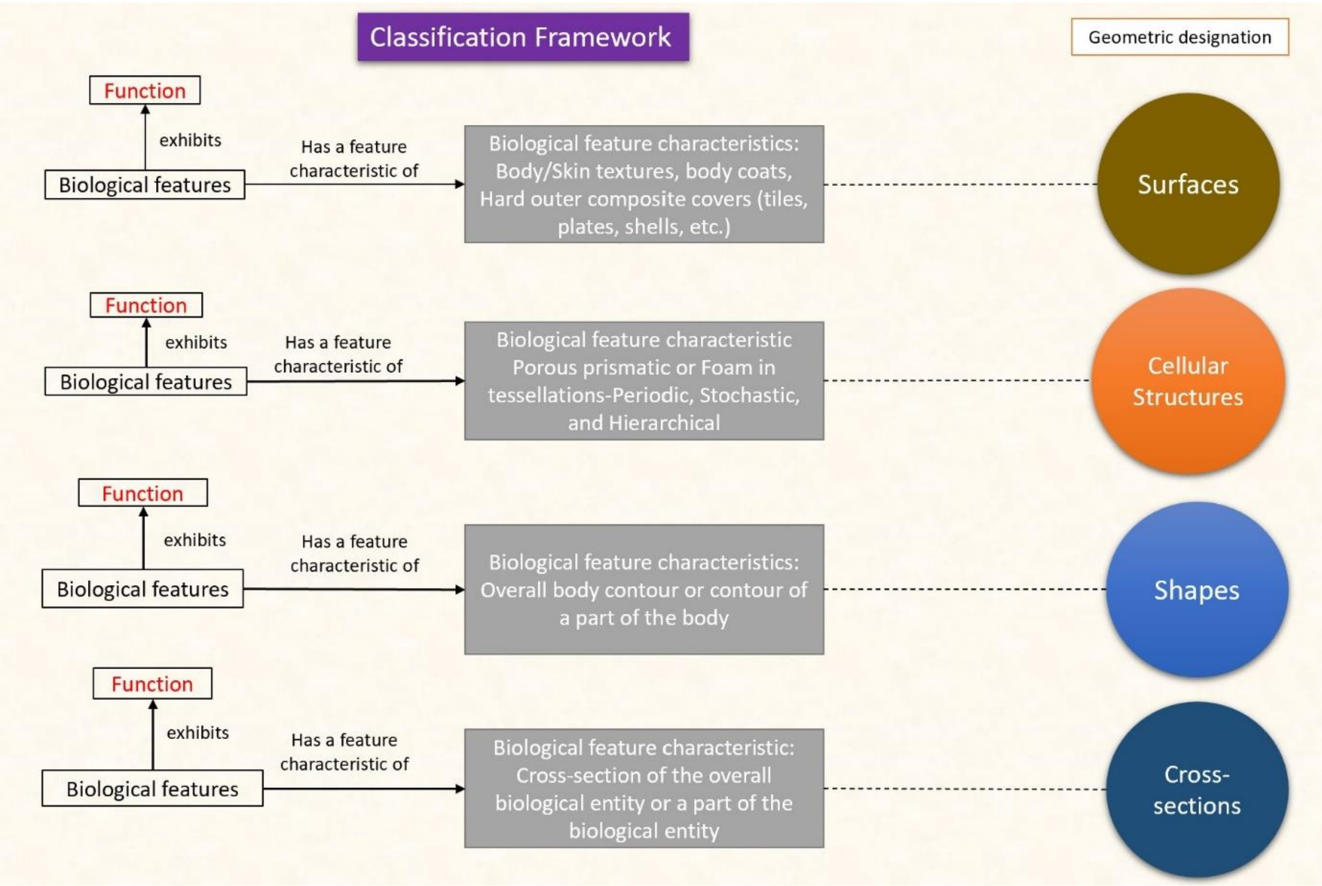

Figure 2. Classification framework to facilitate the biological features into their respective domain (geometric designations).

In nature, biological functions are achieved by combining one or more different biological features, a single feature that can be described as a combination of multiple feature characteristics, or by a combination of one or more other tissues [29]. For example, the boxfish's shape reduces drag because its overall shape is formed by the combination of skeletal connective tissue and muscular tissue. Likewise, the rotational parabolic cross-section observed in the kingfisher's beak can be described by two biological characteristics, namely the hard outer cover (plate), and the inner bone (cellular structure).

Therefore, it is tough to classify biological features systematically into a finite number of domains. To facilitate such complex classifications, cross-sections, and shape domains are considered sub-domains of surface and cellular structures, as they have associated biological feature characteristics belonging to the surface or cellular-structure domains.

In previous research, the DID method classified biological features into four domains: surface, cellular structure, shape, and cross-section. However, it is observed that functions in biological systems are achieved by combining multiple features (multiple tissues) or features described by combining different feature characteristics. For example, the beak of a toucan exhibits resistance to bending due to a combination of multiple feature characteristics such as an outer keratinous plate combined with stochastic tessellation (spongy bone) [30]. Such complex structures are hard to classify. Biological features are highly complex structures and cannot be described by one characteristic, making it impossible to systematically classify the biological features into a finite number of domains. To facilitate the classification of complex biological features, the xDID model enables the creation of new domains for the biological features with feature characteristics that do not fit into the current domain definitions. The expansion of the existing domains makes the DID model into the Expandable Domain Integrated Design (xDID) model. The following subsection presents the mapping of the biological features to the respective tissues from which they originated, thus mapping the domains that represent different biological features performing various functions to their tissues with a common designation.

Mapping of Biological Features and Domain Definitions

Mapping biological features to their respective tissues requires understanding the principles of the biological world. This section highlights the structural hierarchy of biological systems and details the functions of tissues in animal and plant kingdoms. Firstly, the study by Marshall [31] reported that cells develop their structure and shape based on three factors, namely, inheritance from the mother cell, protein-protein interactions, and from a self-assembly process. After attaining a specific structure, similar cells combine to form a tissue that performs a function. A group of tissues combines to form an organ, and organs combine to form an entire organism [32]. Below is a brief discussion about the types and functionalities of plant and animal tissues derived from the literature on plant anatomy [33] and animal anatomy [34]. Plant tissues are categorized into four types: meristematic tissues, simple permanent tissues, complex permanent tissues, and epidermis.

- Meristematic tissues are responsible for growth in plants. These tissues are primarily present at the tips of the roots and stem in the plant.
- Simple permanent tissues are responsible for storing food and energy. The simple permanent tissue comprises parenchyma, collenchyma, chlorenchyma, aerenchyma, and sclerenchyma, each with its specific function.
- Complex permanent tissue is responsible for the transportation of food and water. These tissues are also called vascular tissues and are formed by combining different types of cells. The most common examples of complex permanent tissue are the xylem and phloem.
- Epidermis tissue is responsible for protecting plants from the external environment. The epidermis in plants comprises a single layer of continuous cells. Examples of the epidermis are hair-like structures at roots for water absorption, spines on the stem, and waxy coatings to prevent excessive water evaporation.

In the animal kingdom, animal tissues are categorized into four types: connective tissues, muscular tissue, epidermis and epithelial tissues, and nervous tissue.

- Firstly, connective tissue performs the function of providing a framework and structural support. Connective tissue comprises dense connective tissue for the connection between bones, areolar tissue for the connection between skin and muscle, and skeletal tissue for the framework. Adipose tissue for mechanical shock absorption and fluidic tissue mainly contain red blood cells (RBC) to transport oxygen and white blood cells (WBC) to maintain the immune system.
- Secondly, muscular tissue is responsible for performing the functions of movement and locomotion. Muscular tissue comprises skeletal muscles, smooth muscles, and cardiac muscles.

- Thirdly, epithelial and epidermis tissue mainly performs the function of protection and defense. Epithelial tissue acts as a skin to the internal organs.
- Finally, nervous tissue carries information from all parts of the body to the brain, and from the brain to all parts of the body.

Inspiration from natural systems enables the generation of product concepts [35]. To achieve this, it is necessary to consider different levels of abstraction of a biological system and the functional interactions. Furthermore, integrating elements from different biological systems requires an understanding of biological and natural materials [36]. This unique classification and mapping method minimizes the gap between biology and technology, which can greatly facilitate design concept generation. The features observed in biological systems are primarily adaptations developed by biological systems, mostly occurring at the tissue level. The mapping of the biological features to their respective tissues from which they originate helps product designers to better understand structural features, and the material aspects enable a better understanding of the biological features. Figure 3 shows a complex network map of the biological feature characteristics classified into domains mapped to their respective tissues developed in this research. As shown in Figure 3, from the surface domain, the micro/nano projections of the lotus leaf repel water droplets using their epidermis tissue [37], while snakes use the scales on their skin for effective friction on high terrain regions, which is mapped to epidermis/epithelial tissue [38]. Similarly, from the cross-section domain, the kingfisher's rotational parabolic beak structure, which achieves a reduction in rupture, is mapped to the connective tissue (beak bone) and epidermal tissue (keratinous layer) [39]. Reducing rupture/puncture is achieved by combining two tissues, connective and epidermal.

The following are the definitions of each domain derived from the biological and geometric designations. Each domain definition is followed by a schematic representation of the classification and mapping of biological features and their characteristics.

Surfaces: The surface domain comprises the biological features with the characteristics that are described in Section 2 of the manuscript. The tissues mapped to the domain in general (classified so far) comprise the epidermal and epithelial tissue of plant and animal kingdoms, and enamels that extend the epidermal tissue and surface layers formed due to molecular self-assembly. In addition, they include external structural features formed by connective tissues from the animal kingdom. Examples in the surface domain include the epidermal tissue in lotus leaves [37], enamel in sharkskin [40], differently oriented surface layers in conch shells [26], and keratinous structures [38].

Figure 4 shows the schematic of classifying biological features with their feature characteristics into domains and mapping the biological features to their biological tissues. As shown in Figure 4, the biological feature of the lotus leaf for its superhydrophobic property is due to the integrated structure; that is, its micro/nano projections. The biological feature characteristic is the body/skin texture and is classified as belonging to the surface domain. The biological feature is mapped to the epidermal tissue in the plant kingdom. Similarly, the snakeskin manages friction by its biological feature; that is, its scales [41]. Its biological feature is characteristic of body/skin texture, which is classified as surface and mapped to the animal kingdom's epidermis tissue [38]. Likewise, the mollusk shell's ability to absorb energy is due to its biological feature; that is, its outer shell [2]. It has a feature characteristic of a hard outer cover, which is classified as surface domain and mapped to the connective tissue [42]. The gecko's ability to stick to a surface is due to its biological feature; that is, its hair [38]. It has a characteristic body coat that is classified as a surface domain and mapped to the animal kingdom's epidermal tissue [43].

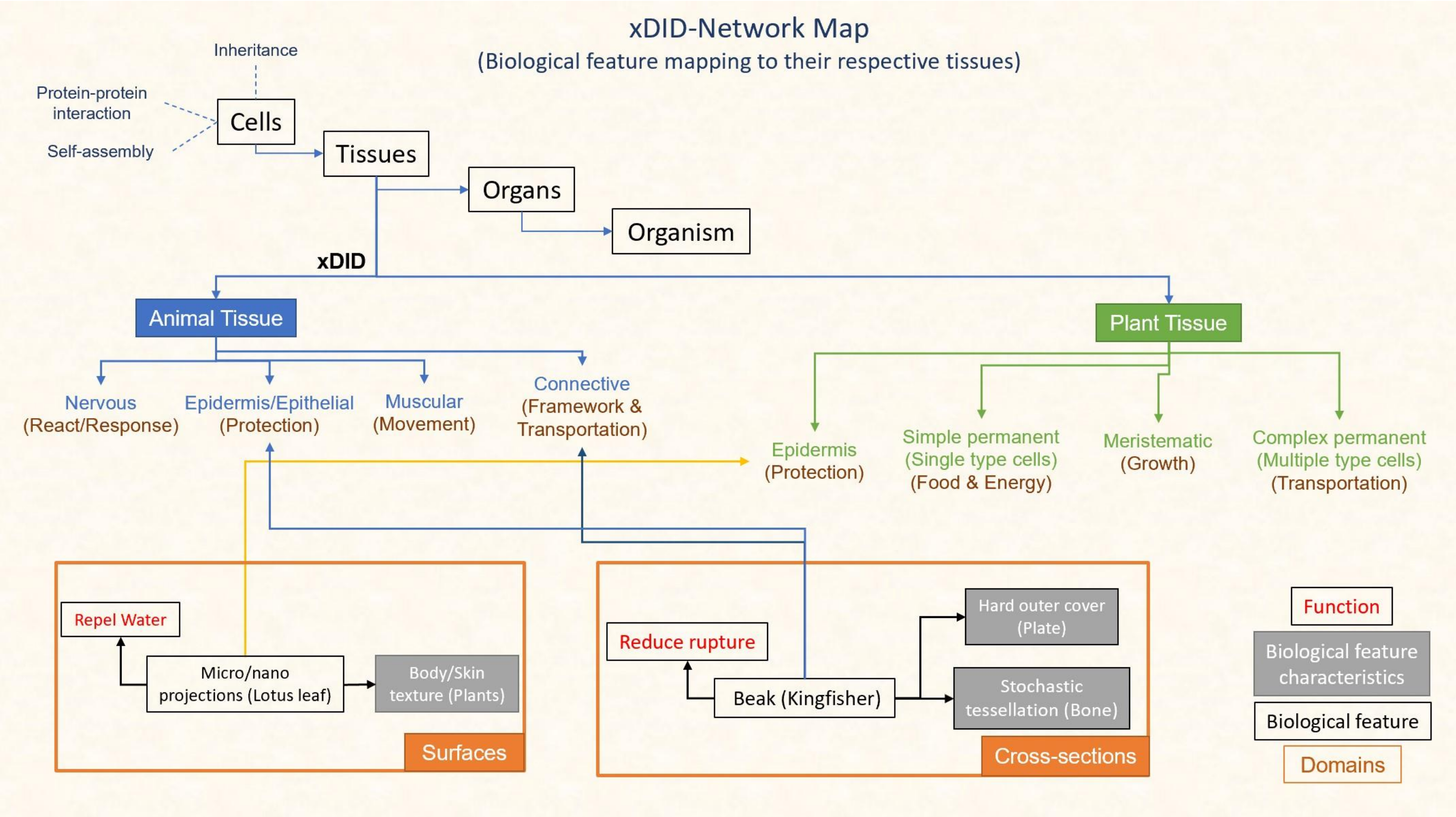

Figure 3. Network map of biological features and their characteristics to their respective tissues.

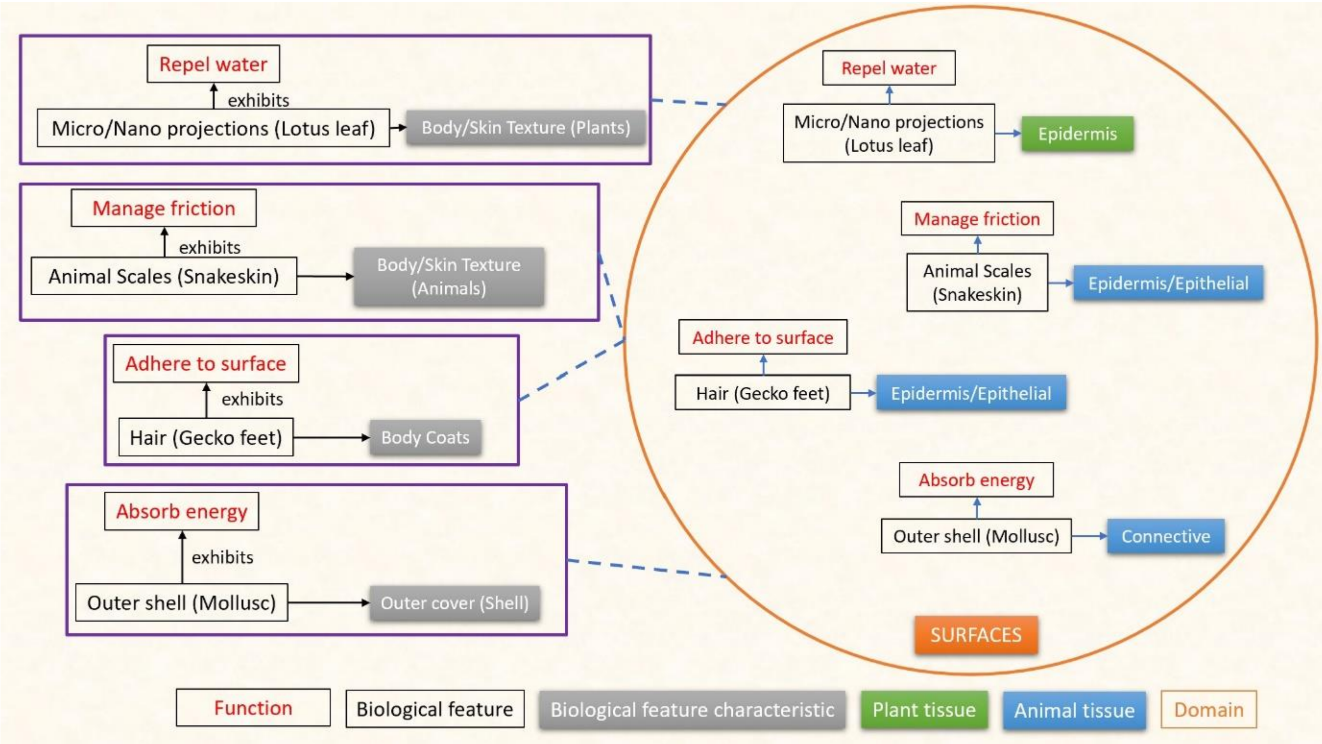

Figure 4. Schematic of the classification and mapping of the biological feature and biological feature characteristics to the surface domain and their corresponding tissues.

Cellular structures: The cellular structure domain comprises the biological features with characteristics that are described in Section 2 of the manuscript. The tissues mapped to this domain in general (classified so far) comprise the simple permanent tissue in the plant kingdom and connective tissue from the animal kingdom.

Figure 5 shows a schematic classifying biological features and their characteristics to their domains and mapping the biological feature to its corresponding tissue. As shown in Figure 5, waterlily leaves exhibit resistance to bending due to their biological feature that is the leaf, and the biological characteristic is hierarchical tessellation which is the branching of the stem [14]. Waterlily leaves are classified as cellular structures and mapped with the plant kingdom's simple permanent tissue (sclerenchyma of the simple permanent tissues provides mechanical support to the plant body) [44]. Likewise, the pomelo peel exhibits resistance to impact due to its biological feature that is the peel, and has a biological feature characteristic of stochastic tessellation [45]. Pomelo peel is classified as a cellular structure and is mapped to the simple permanent tissue in the plant kingdom [46].

For the cross-section sub-domain and the shape sub-domain, the function exhibited is due to a combination of different biological characteristics, or a combination of different biological tissues. The cross-section and shape sub-domains have an associated biological feature characteristic belonging to either the surface or the cellular structure. The following are definitions and elaborations of the sub-domains, with the schematic showing the classification and the mapping to their respective tissue.

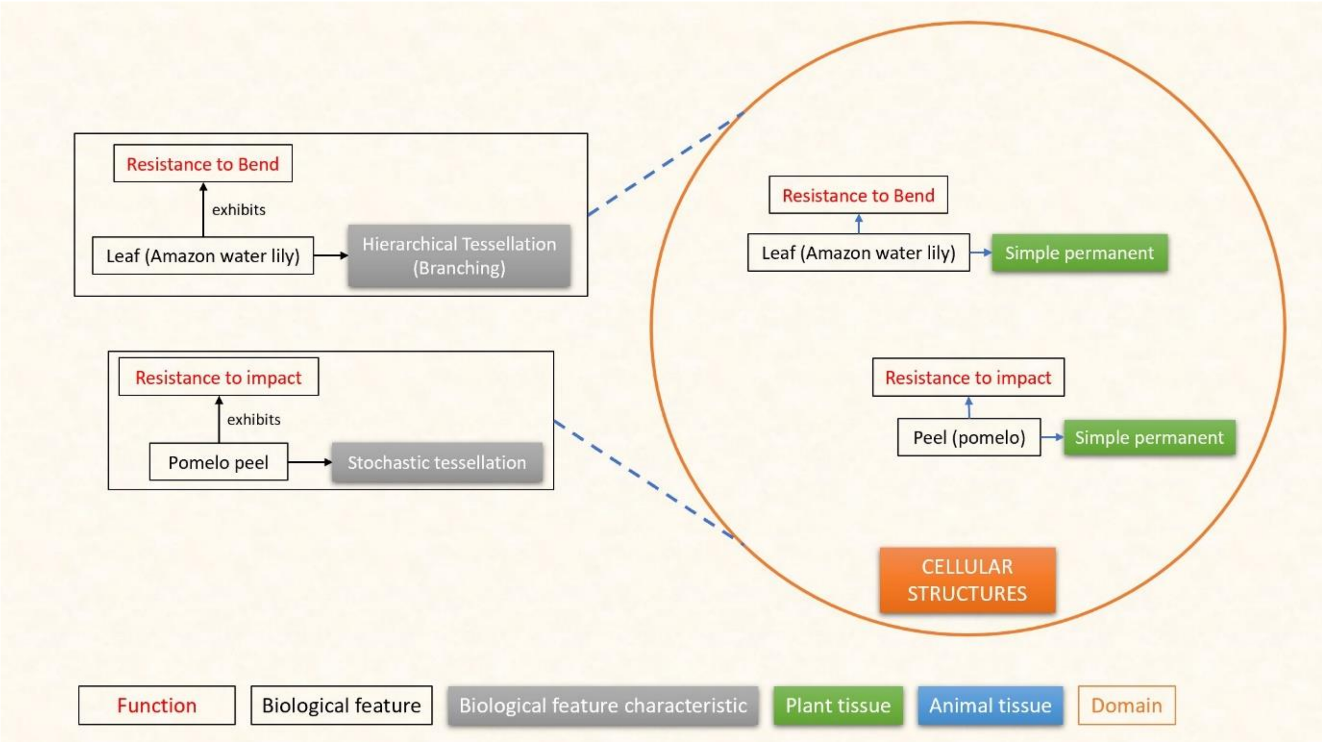

Figure 5. Schematic of the classification and mapping of the biological features and biological feature characteristics to the cellular structure's domain and their corresponding tissues.

Cross-section: The cross-section domain comprises the biological features with the characteristics that are described in Section 2 of the manuscript. In other words, cross-sections are defined as the shape obtained by the intersecting plane with a solid body in a three-dimensional space. The tissues mapped to this domain in general (classified so far) comprise meristematic tissue, complex permanent, and simple permanent from the plant kingdom, and connective tissue from the animal kingdom. Figure 6 shows the schematic classification of the biological features and their characteristics to the cross-section domain and the mapping of the feature to its corresponding tissue. As shown in Figure 6, the biological feature of bamboo tree stem cross-section exhibits absorb energy [2] by a combination of biological tissues, namely simple permanent, complex permanent, and meristematic tissue. The stem cross-section is classified as the cross-section domain due to its biological feature characteristic which is a cross-section of the body parts. The vascular stochastic foam structure is formed as a combination of the meristematic, simple, and complex permanent tissues [44]. Likewise, the kingfisher's beak exhibits a reduction in puncture force due to its biological feature; that is, its rotational parabolic cross-section [24,28]. The reduction in puncture force is achieved by combining biological feature characteristics, such as plates and foamy bone. The kingfisher's beak cross-section is classified as belonging to the cross-section domain, and the biological feature characteristic, consisting of the hard outer plate, is mapped to epidermis/epithelial tissue in the animal kingdom, while the inner bone is mapped to the connective tissue [47].

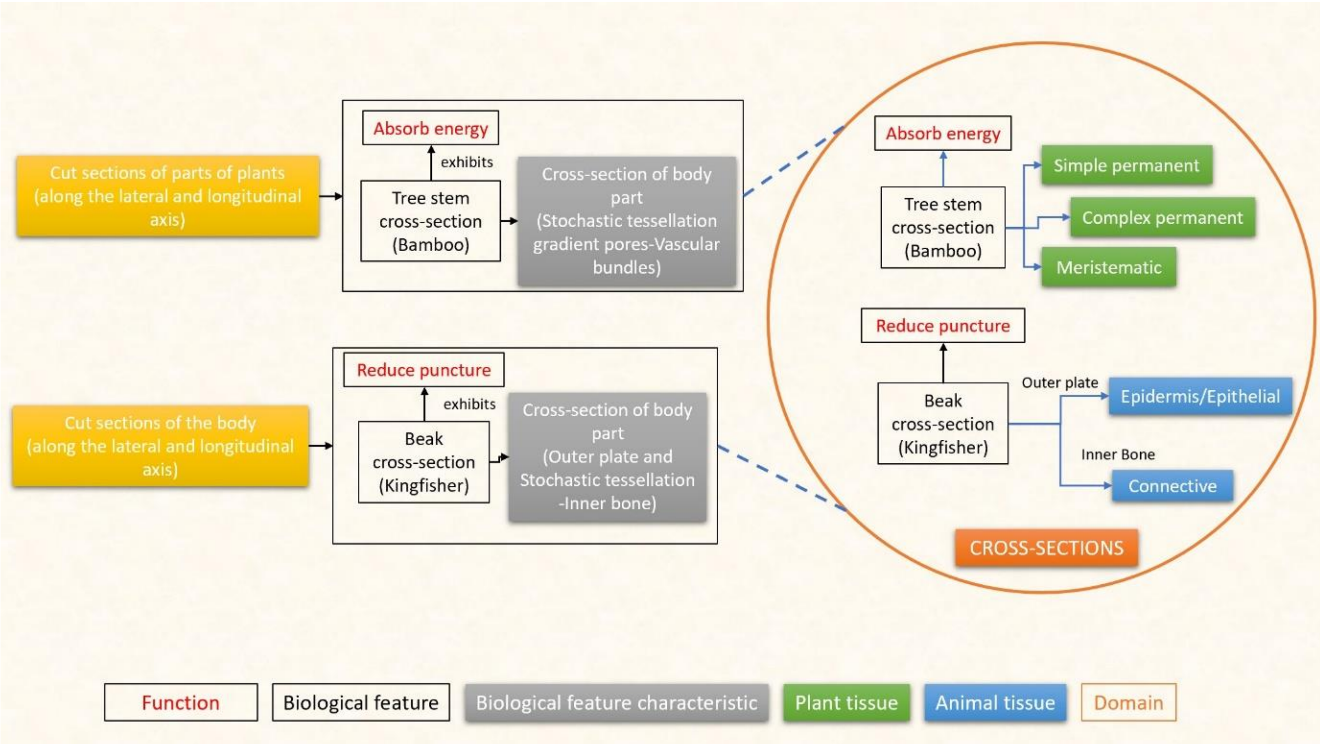

Figure 6. Schematic of the classification and mapping of the biological feature and biological feature characteristics to the cross-section's domain and their corresponding tissues.

Shape: The shape domain comprises the biological features with the characteristics that are described in Section 2 of the manuscript. The tissues mapped to this domain in general (classified so far) include meristematic tissue from the plant kingdom, and muscular and connective tissue from the animal kingdom. Mathematical definitions of shapes are symmetrical and can be further divided into axial, bilateral, and radial symmetry [48]. Shapes can also be asymmetrical, such as in basking sharks, which change their jaw geometry to an asymmetric shape to catch fish with minimum energy [49].

Figure 7 is the schematic of the classification of the shape domain. The reduced drag function is achieved by the biological feature which is the overall shape (spindle) of the penguin [50] that has a biological feature characteristic of a full body contour. However, the shape of the body of a penguin is achieved by the combination of muscular and connective tissues [50]. Biological features and their characteristics are mapped to the muscular and connective tissue in the animal kingdom.

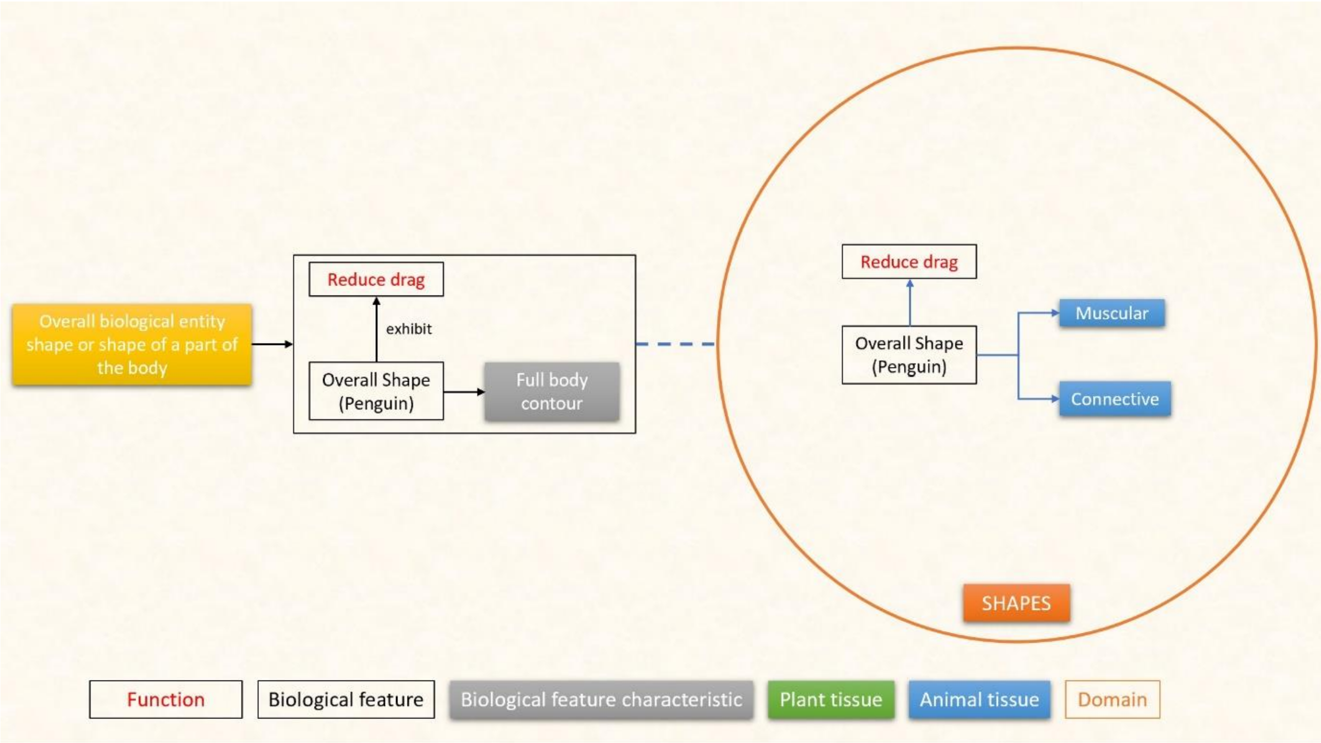

Figure 7. Schematic of the classification and mapping of the biological features and biological feature characteristics to the shape domain and their corresponding tissues.

3. Understanding Functions in Biological Systems and Their Definition in xDID

Lienhard et al. [51] identified that the criterion for describing a natural system is the combination of form, material, and function. Ren and Liang [8] elucidated that biological functionality is achieved by combining or coupling and interacting with various factors or elements such as morphologies, structures, materials, and the constitution of an organism. For example, the lotus effect or self-cleaning mechanism combines non-smooth morphology, micro-nano composite structures, and waxy materials. On a broader perspective, the coupling elements or factors are classified as physical coupling elements that consist of physical forms such as material, structure, and shape, and non-physical coupling elements that consist of biological behavior such as flexibility, lubrication, etc. In realizing the combinations of factors or elements responsible for achieving functionality, Ren and Liang [9] discussed earthworms that resist adhesion through lubrication, electro-osmosis, non-smooth morphology, and flexibility provided by the synergetic interaction of various body parts. Similarly, digging mole crickets are able to reduce friction, resist adhesion, and resist wear due to the shape, structure, and surface of their forelegs, forewings, and tergum. Gao [52] presented that the difference between two distinct biological entities that exhibit similar functionality is the change in their surface microstructures. For example, mosquito eyes and lotus leaves show the same property of superhydrophobicity, and each biological entity has a different microstructure and arrangement that achieves the same functionality. This explains that a specific property/functionality depends on the microstructure and the arrangement or configuration of microstructures. In a study by Helfman Cohen et al. [49], over 140 biological systems were analyzed using a complete viable model which provided a list of structural–functional patterns that repeat in biomimetic applications. The repeated patterns are protrusions, tubes/channels, asymmetry, layers, intersected layers, helixes, streamlined shapes, and containers. Although the study included a proposed Su_field model for representing the function achieved through the structure in terms of an engine, transmission, control, and working unit, the study did not include a method for classification or mapping and function abstraction techniques for the integration and generation of multifunctional conceptual designs. The following sub-section provides the details of function abstraction in the xDID model.

Meta-Level Embodiment Function

Functions in products and systems can be described as overall, embodiment, and geometric functions. The overall function represents the generic description of an intended purpose achieved by combinations of different system components. Meanwhile, the embodiment level describes the functions of components, and the geometric level describes the detailed geometric feature [53]. However, the fundamental mechanical function can be described as the level of embodiment function. Functions at this level are associated with the physical structure. The structure at this level represents the physical characteristics of a product. Previous research on biological analogy abstraction used functional modeling or function representation techniques to understand the overall functions of the biological system. Abstraction frameworks such as SAPPhIRE [54] and DANE (SBF) [55] represent biological systems using similar techniques to those used in functional modeling. The functional modeling technique analyses a complex physical product or a system involving connections between various components, substances inside components, pre-conditions and post-conditions, and state changes and transitions [55]. Function modeling is an expression, representation, or description of a product or system using high-level abstract language depending on its functionality [56]. The systems can be described as process flow block diagrams or hierarchical tree models of functional behavior [57]. However, in the xDID model, adopted from the definition of embodiment function by Deng et al. [53], the function is proposed at the level of the embodiment function (physical structure level), which is achieved by the combination of the integrated structure (often multiscale) and its structural strategies. This approach is a meta-level description of the biological feature and its associated structural strategy. The descriptions of integrated structures (multiscale) and the structural strategies are as follows:

- The integrated structure (multiscale) is proposed as the physical description of the multiscale structure (e.g., micro/nanostructure, macrostructure, and the presence of wax layers on the structure, etc.).
- The structural strategy is proposed as the integrated structural configuration (e.g., arrangement of the micro/nanostructure, packing of the micro/nanostructure, orientation of micro/nanostructure, symmetry, asymmetry, or patterns of tessellations, etc.) and change in the structural configuration due to stimulus. Stimulus occurs when the other interacting elements connect to the structure (e.g., erection of scales, change in skin compliance, etc.).

Often biological systems exhibit functions by utilizing different structures and strategies, or a combination of different structures and strategies. However, the structural strategy in the xDID model is defined as a configuration of the structure in terms of the arrangement, orientation, packing, symmetry, or asymmetry of various structures or various patterns of tessellations, and changes in the configuration of the structure due to external stimuli. Figure 8 shows a schematic representation of the meta-level embodiment function exhibited by biological features in the xDID model. The representation of the embodiment function as a combination of the integrated structure and the associated structural strategy of two biological features is shown in Table 1 As shown in Table 1, the lotus leaf's repel-water function and self-cleaning properties are realized by its pointed micro-nano composite structure and waxy materials arranged randomly across the leaf. Similarly, the micro bumps and grooves on the scorpion skin exhibit resistance to erosion and have a similar structural strategy of random microstructure arrangement. Often it is also observed that the embodiment functions exhibited by distinct biological features have a similar structural strategy, as shown by the examples in Table 1. The ones in bold *italics* represent the crucial strategy for exhibiting a particular function.

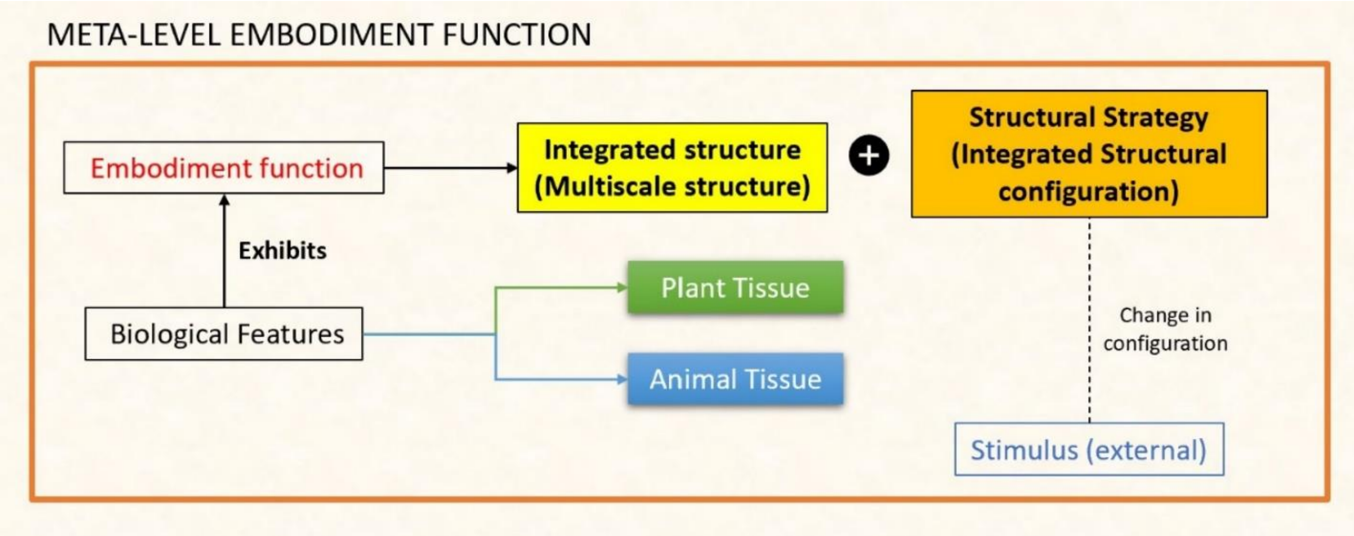

Figure 8. Schematic of the meta-level embodiment function.

Table 1. An example of the embodiment functions of biological features represented as a combination of the integrated structure and its associated structural strategy.

Meta-Level Embodiment Function	Biological Feature	Biological Feature Characteristic	Integrated Structure	Structural Strategy
Repel water	Micro/Nano projections (Lotus Leaf)	Body/Skin Texture (Plants)	Microstructures covered with wax layers. The microstructures are often pointed in shape [13]	***Random arrangement*** of the micro perturbances [52]
Resistance to erosion	Micro/Nano projections (Desert scorpion)	Body/Skin texture (Animals)	Microstructures, grooves, and bumps on the surface can improve anti-erosion performance [58]	***Random arrangement*** of the micro bumps [58]

As discussed earlier, biological features are complex; classifying them based on feature characteristics is a complicated process, and the current number of domains might not be sufficient to fit every biological feature. The wide variety of biological features makes it extremely tough to classify them as belonging to a particular set of defined domains. However, the xDID model is an attempt to accommodate complex biological features by adding more domains and creating micro-domains within the same domain that offer more accurate descriptions and classifications of biological features by their characteristics. As shown in Figure 9, the micro-domain for surfaces will be outer composite tiles, outer composite plates, and outer composite shells, as they have complex composite structures. Similarly, the micro-domains for cellular structures will be by the kind of connection in the tessellations, such as beam-based or face-based connections. The cross-section sub-domain has the cross-sections that are formed due to composition or by sandwiching two or more different structures; for example, a combination of the outer plate and internal muscular and bone structures. The creation of micro-domains aims to enhance the ideation process.

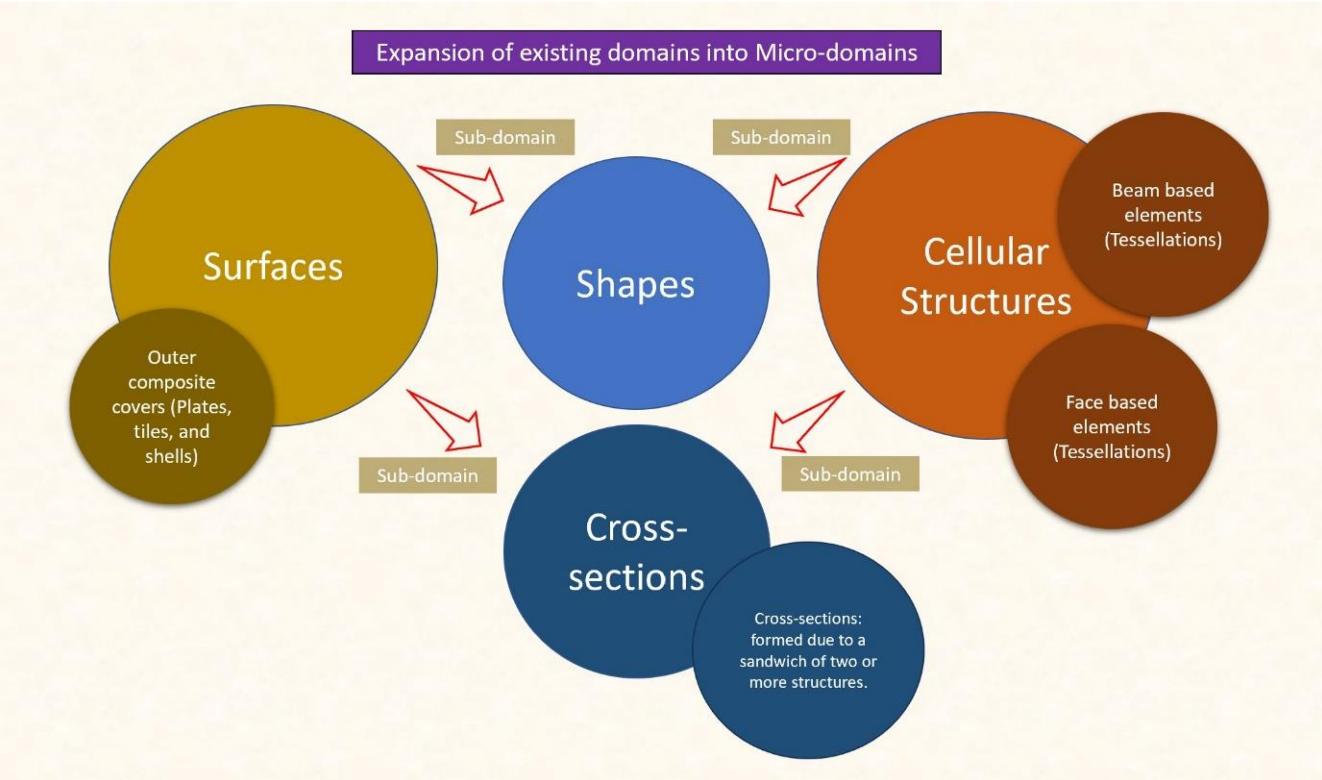

Figure 9. Creation of micro-domains in surfaces and cellular structures.

4. The xDID Model and Its Applications

Biological systems are multifunctional, meaning they perform multiple functions simultaneously. However, functions in biological systems are achieved by their unique features developed during evolution. Combining different features inspired by different biological systems is necessary for the creation of uncommon and unique multiple functions simultaneously. As discussed earlier, the xDID model facilitates the process of combining different biological features by classifying (currently) around 50 biological features abstracted from case studies into their geometric designations called domains and mapping them to the respective tissues from which they originate. The xDID model is an integration of the previously introduced classification and mapping of biological features and the representation of the embodiment function into a systematic approach. The combination of biological features from different domains aids in the creation of multifunctional design concepts.

As shown in Figure 10, firstly, the biological features are classified by their feature characteristics into their respective geometric designations, called domains. Domains represent different biological features performing various embodiment functions, mapped to their tissues with a common geometric designation. Shapes and cross-sections are considered the sub-domains of surface and cellular structures because they have an associated biological feature characteristic belonging to the surface or cellular-structure domain. Secondly, each biological feature is mapped to the respective tissues from which they originate. Thirdly the embodiment function of the biological feature is represented as a combination of the integrated structure and its structural strategy. The sub-sections provide the case studies developed for the validation of the xDID model.

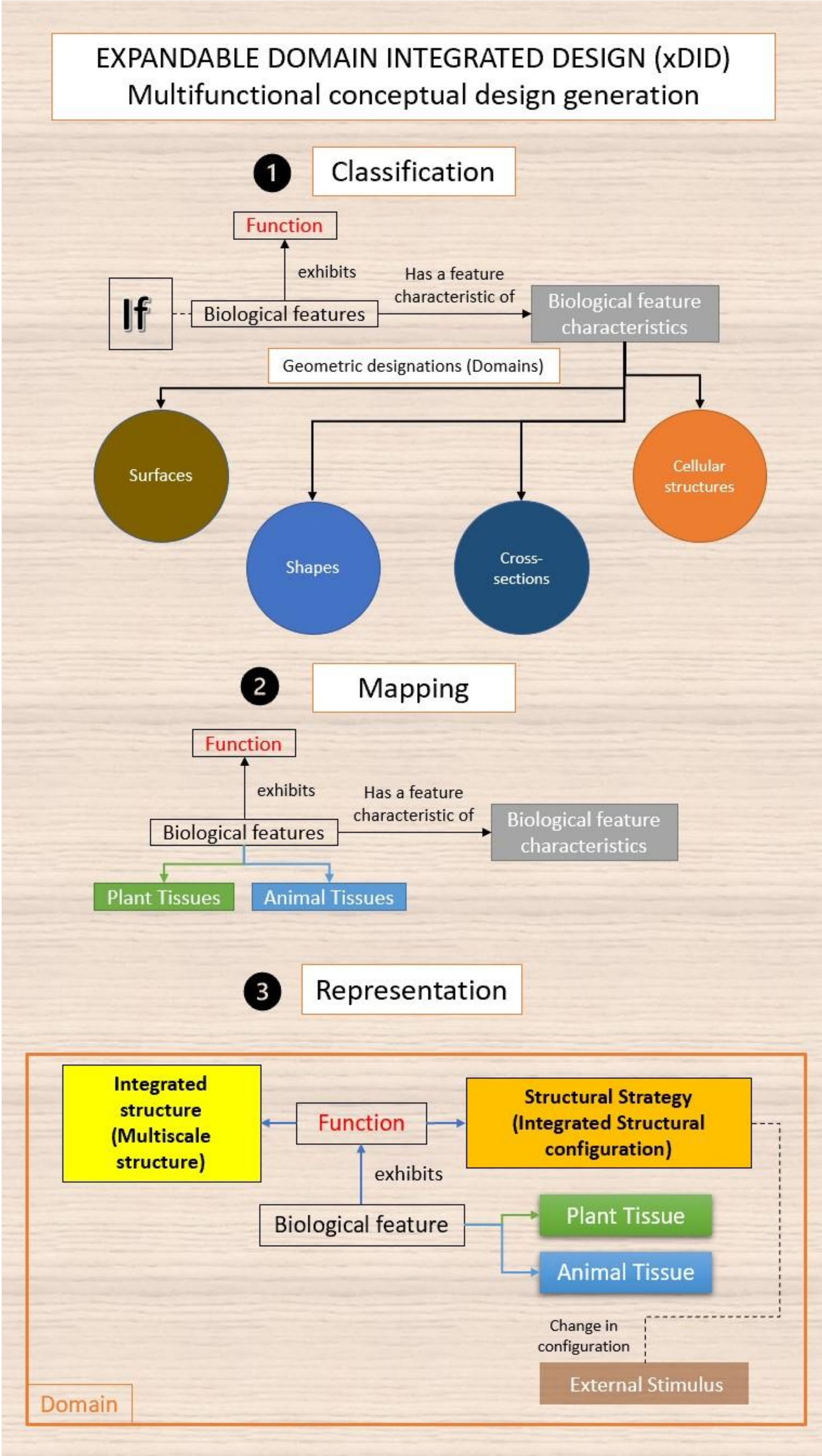

Figure 10. xDID Model.

4.1. Multifunctional Bio-Inspired Painless Sutures

Three multifunctional bio-inspired case studies were carried out as validations of the xDID model. Firstly, the creation of painless sutures [24] is generated by the combination of a cross-section of the kingfisher's beak and the barbs on porcupine quills. Kingfisher beaks have biological features characteristic of the cross-section of the body part formed as a combination of an outer plate and stochastic tessellation (inner bone), and are classified as belonging to the cross-section domain. Porcupine quill barbs have biological features characteristic of body/skin texture, and are classified as belonging to the surface domain. The sutures perform two embodiment functions (reducing puncture force and resisting retraction) which reduce external disturbance. Figure 11 shows a schematic sketch and CAD model of the generated painless sutures.

Figure 11. Multifunctional sutures inspired by the kingfisher's beak and porcupine quills [24].

The design generation involved the following sequence.

(a) *Classification:* Figure 12 shows the classification of the kingfisher beak's cross-section, having the biological features characteristic of a cross-section of the body part and is formed from the combination of hard outer plates and stochastic tessellation (inner bone). Figure 13 shows the mapping of the kingfisher's beak to its respective biological tissue. The kingfisher's beak cross-section is classified as the cross-section's domain. Similarly, as shown in Figure 14, the micro/nano projections of bars on the porcupine quills with features characteristic of body coat/modified hairs are classified as surface domain.

(b) *Mapping:* The classified biological features are mapped to their respective biological tissues. The outer plate of the kingfisher's beak is mapped to the epidermis/epithelial tissue and the inner bone with the stochastic tessellation is mapped to the connective tissue [47]. Similarly, the bars on the porcupine quill are mapped to the keratinous material (connective tissue) [59]. Mapping biological features to their respective tissues enhances the understanding and application of the structural and material aspects of the feature. It initiates and ensures the search for appropriate material selection for the new design that matches the properties of biological materials. Figure 13 shows the mapping and the materials that make up the kingfisher's beak cross-section, which are keratins, collagen, and calcium phosphate [60]. However, to make the sutures biodegradable, magnesium metal was chosen for the analysis of the sutures [24]. Similarly, as shown in Figure 15, the barbs of porcupine quills are made of keratins [59].

(c) *Representation:* Figures 13 and 15 show that the embodiment function of the kingfisher's beak (to reduce rupture) is represented as a combination of an integrated structure that is a rotational parabolic cross-section [24] and the strategy or structural configuration that is symmetry along the axis of the beak. The embodiment function of the barbs on porcupine quills (to resist retraction and ease insertion) is represented as a combination of the integrated structure (micro-triangular shaped barbs) and its structural strategy (sequential arrangement, and orientation of the barbs towards the body) [61].

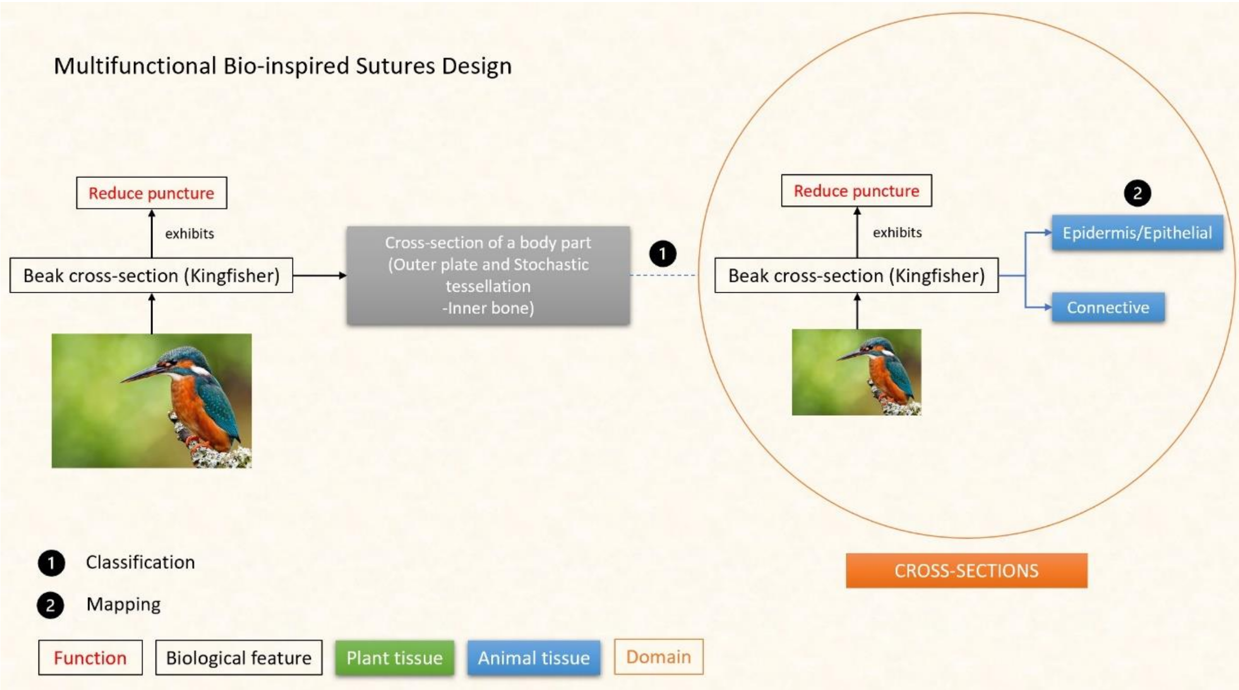

Figure 12. Classification and mapping of the kingfisher beak (cross-section) to its respective domain and the respective tissue from which it *originated*.

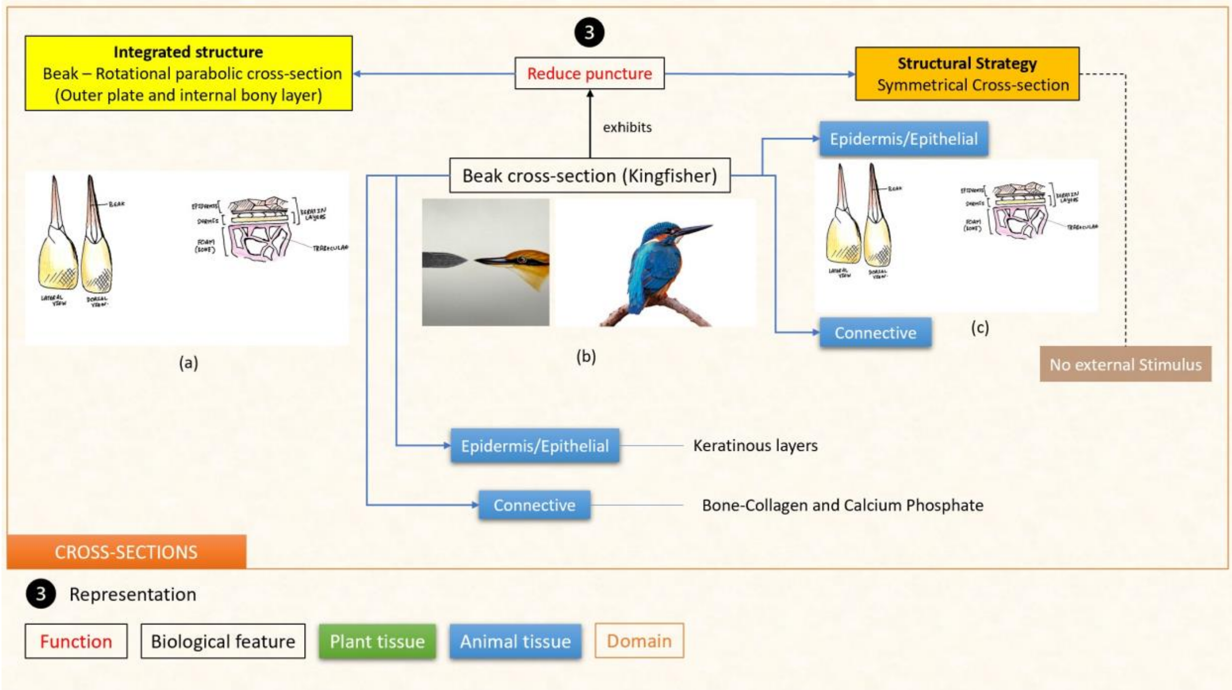

Figure 13. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**) [62], (**b**) [28], and (**c**) [39].

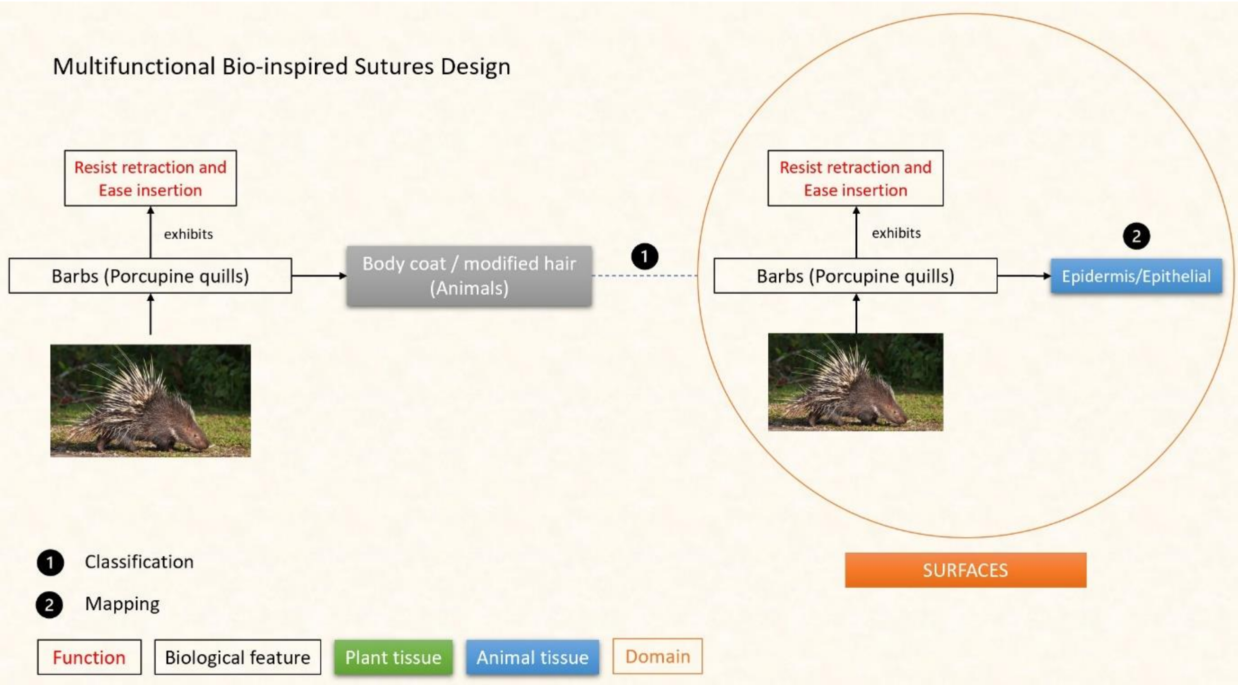

Figure 14. Classification and mapping of the barbs on porcupine quills to their respective domain and the respective tissue from which they originated.

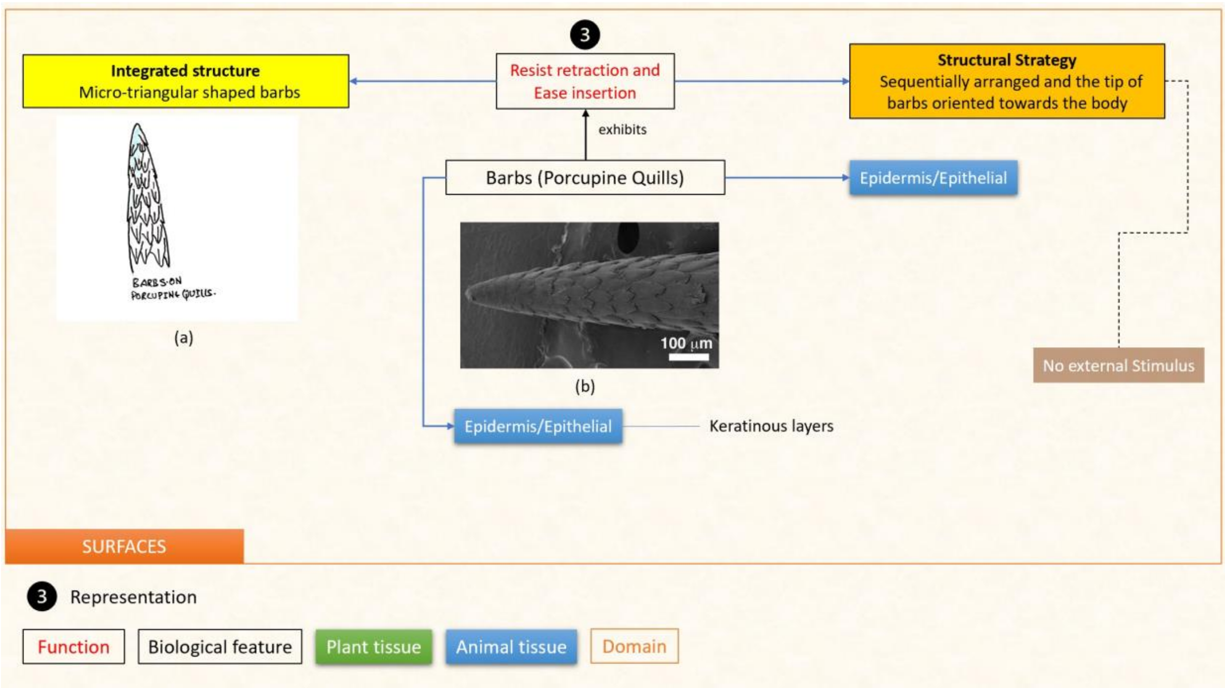

Figure 15. *Representation of the function as a combination of integrated structure and the structural strategy.* Picture inspiration (**a**,**b**) [61].

The final multifunctional design is obtained as a combination of the kingfisher's rotational parabolic cross-sectional structure and the barbs on the surface of the structure.

4.2. Multifunctional Effective Heat Transfer and Low-Pressure Drop

The creation of the low friction factor and highly effective heat transfer is generated by the combination of camel turbinate and the micro bumps on the Namib Desert beetle [63]. The camel turbinate structure with the biological features characteristic of a cross-section of the body part is classified as the cross-section domain, and the micro-bumps on the desert scorpion's skin with the biological features characteristic of body/skin texture are classified as surface domain [63]. Note that the micro bumps of the Namib Desert beetle have the embodiment function of absorbing water from fog. However, inspired by the Namib Desert beetle, micro bumps are added to the surface of the camel labyrinth structure to increase the surface area. Figure 16 shows the structure for highly effective heat transfer and low friction drop inspired by the camel turbinate and the micro bumps inspired by the Namib Desert beetle.

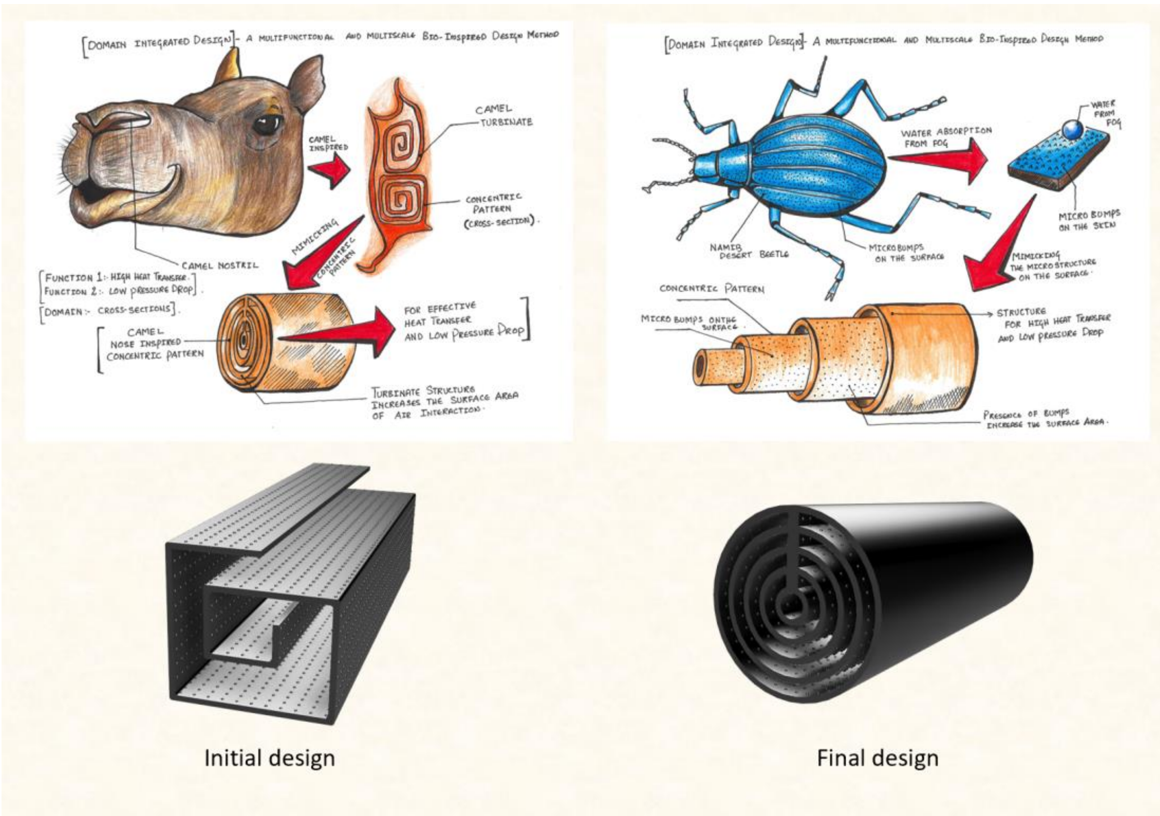

Figure 16. Multifunctional structure for highly effective heat transfer and low friction drop inspired by camel turbinate and the Namib Desert beetle's micro bumps [63].

The design generation of this structure involved the following sequence:

(a) *Classification:* As shown in Figure 17, the camel turbinates cross-section with biological features characteristic of a cross-section of the body part (Nasal cartilage) is classified as belonging to the cross-section domain. Figure 18 shows the mapping of the camel turbinates to their respective tissue. Similarly, Figure 19 shows the micro/nano projections of the Namib Desert beetle with biological features characteristic of body/skin texture, classified as belonging to the surface domain.

(b) *Mapping:* The classified biological features are mapped to the tissues from which they originate. The camel's turbinate (nasal cartilage) is mapped to the connective tissue [64]. Similarly, the micro/nano projections of the Namib Desert beetle are mapped to the epicuticle/epidermis tissue [1]. Figure 18 shows the mapping and the materials of the tissue from which the biological feature is made. Mapping initiates and ensures the search for appropriate material selection for the new design that matches the properties of biological materials. As shown, nasal cartilage is made up of collagen, elastic fibers, and extracellular matrixes (ECM) [65]. Similarly, as shown in Figure 20, the micro bumps of the Namib Desert beetle arise due to the keratin layers of the skin. For this study, the structures are analyzed for convective heat transfer and the material aspects of the structure are omitted.

(c) *Representation:* Figures 18 and 20 represent the embodiment function of the camel turbinate structure (to transfer heat) as a combination of the integrated structure that is a labyrinth [64,66] and the structural strategy is the symmetry along the axis. Similarly, the embodiment function of the Namib Desert beetle's micro bumps (to increase surface area and absorb water) is represented as a combination of the integrated structure; that is, its peaks are hydrophilic, its valleys are hydrophobic, and the structural strategy is the orientation of the micro bumps at 23 degrees to the ground [1].

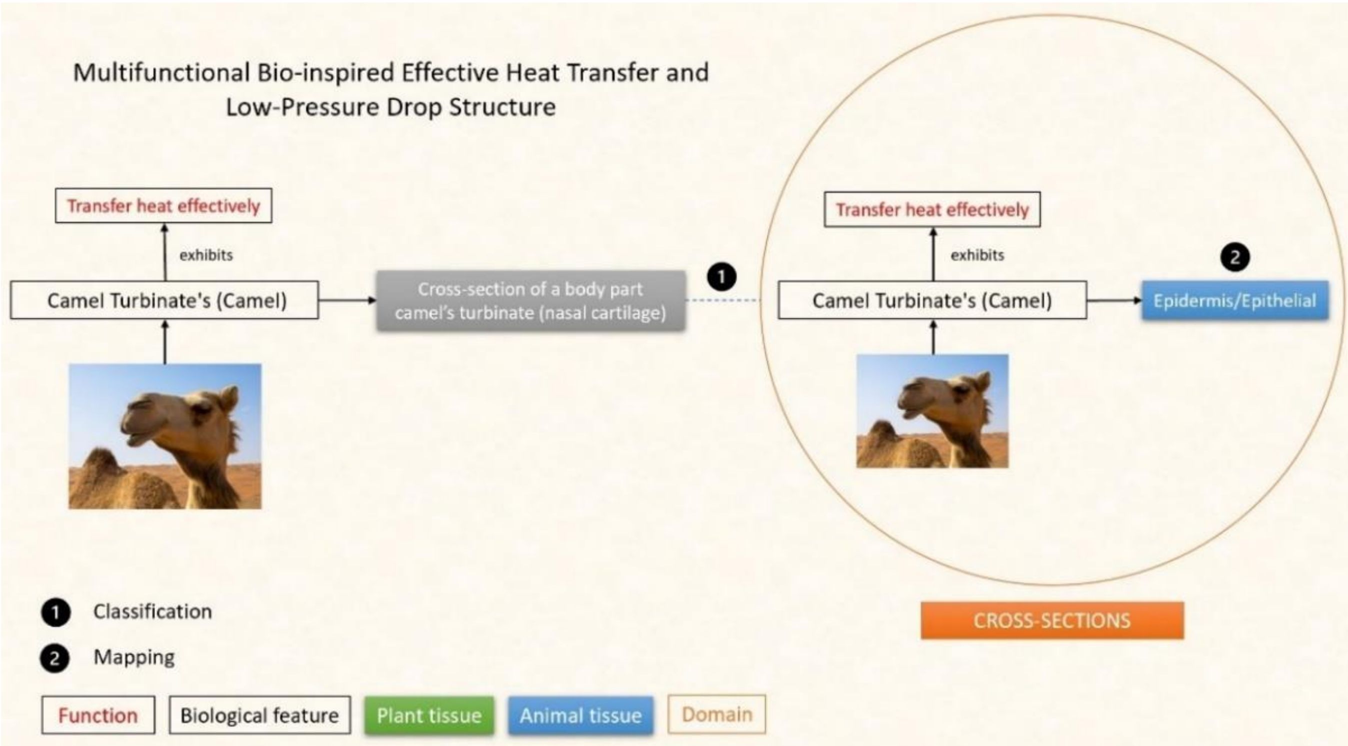

Figure 17. Classification and mapping of the camel turbinate (cross-sections) to its respective domain and the respective tissue from which it originated.

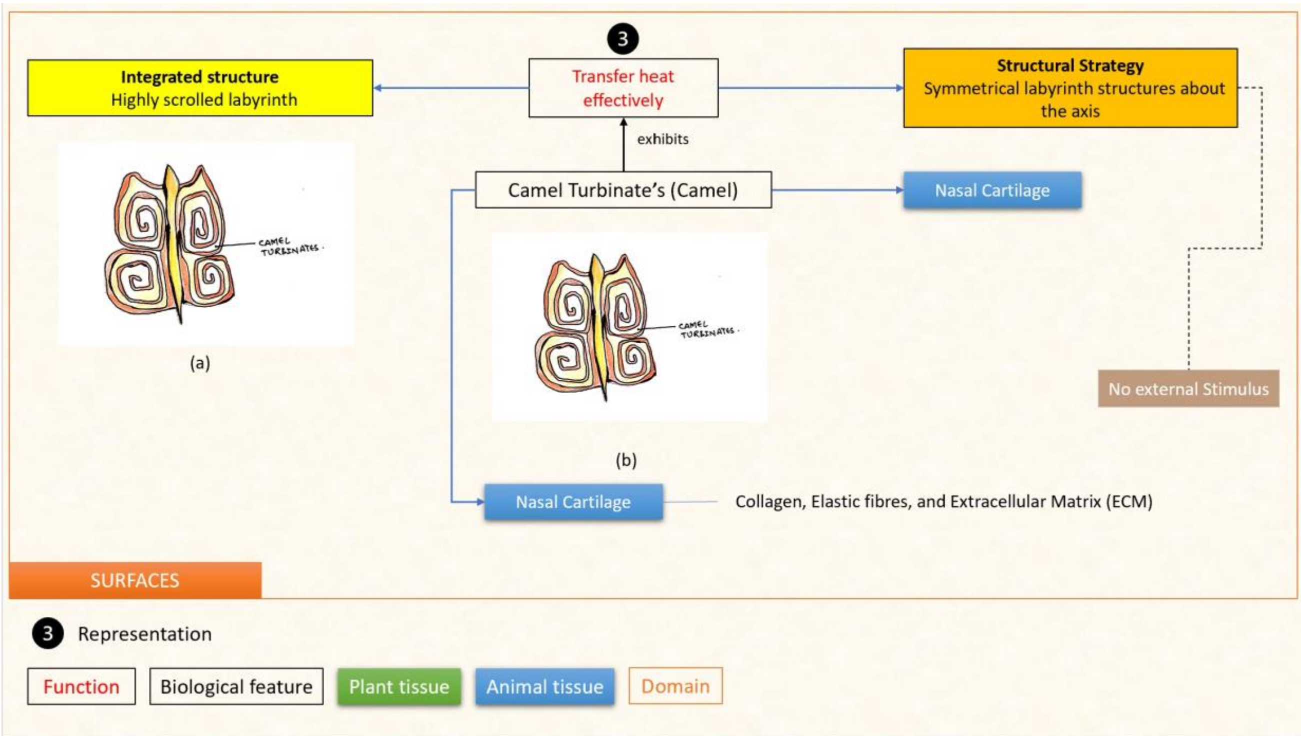

Figure 18. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**,**b**) [64].

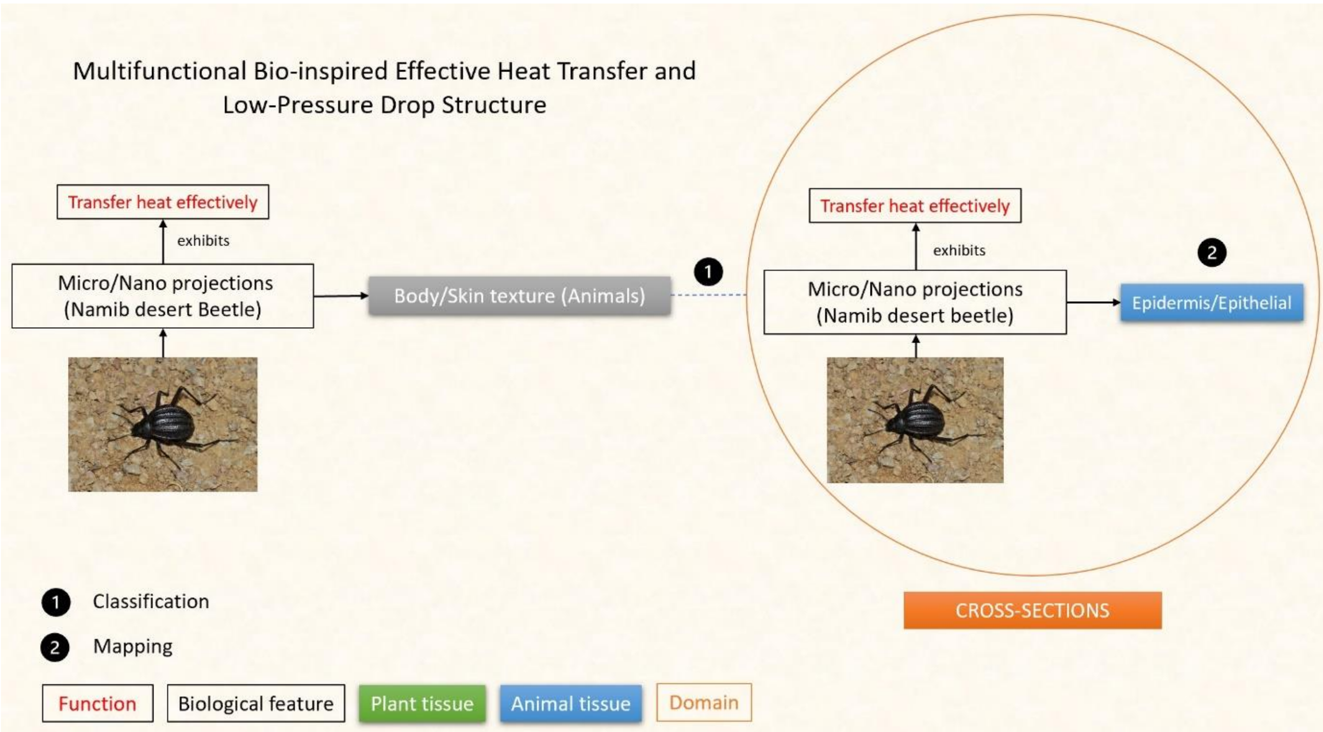

Figure 19. Classification and mapping of the Namib Desert beetle's surface to its respective domain and the tissue from which it originated.

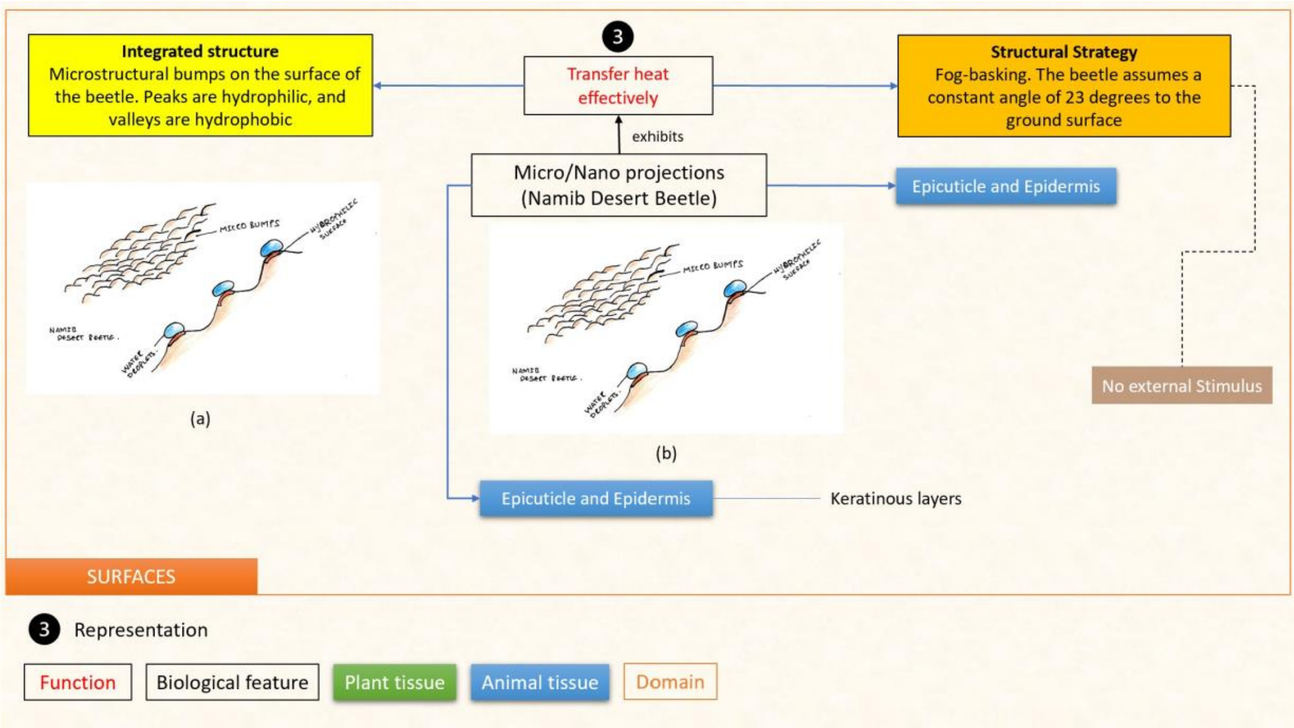

Figure 20. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**) [67] and (**b**) [68].

The final multifunctional design was obtained as a combination of the camel turbinate structure and the micro-bumps on the surface of the Namib Desert beetle.

4.3. Multifunctional Non-Pneumatic Tire Design

Likewise, the multifunctional non-pneumatic tire was designed by combining snakeskin scales with the woodpecker's beak and pomelo peel [69]. Snakeskin scales with the biological features characteristic of body/skin texture are classified as surface domain, and woodpecker's beak foam with features characteristic of stochastic tessellation is classified as belonging to the cellular-structure domain (note that the beak is a composite structure; only the foam feature is considered for this study, and hence classified as belonging to the cellular-structure domain). Pomelo peel structure has biological features characteristic of stochastic tessellation and is classified as belonging to the cellular-structure domain. The multifunctional tire achieves two functions: to manage friction (inspired by snake scales) and to resist impact (inspired by the woodpecker's beak and pomelo peel) [69]. Figure 21 shows a schematic sketch of the multifunctional non-pneumatic tire design inspired by snake scales, the woodpecker's beak, and pomelo peel.

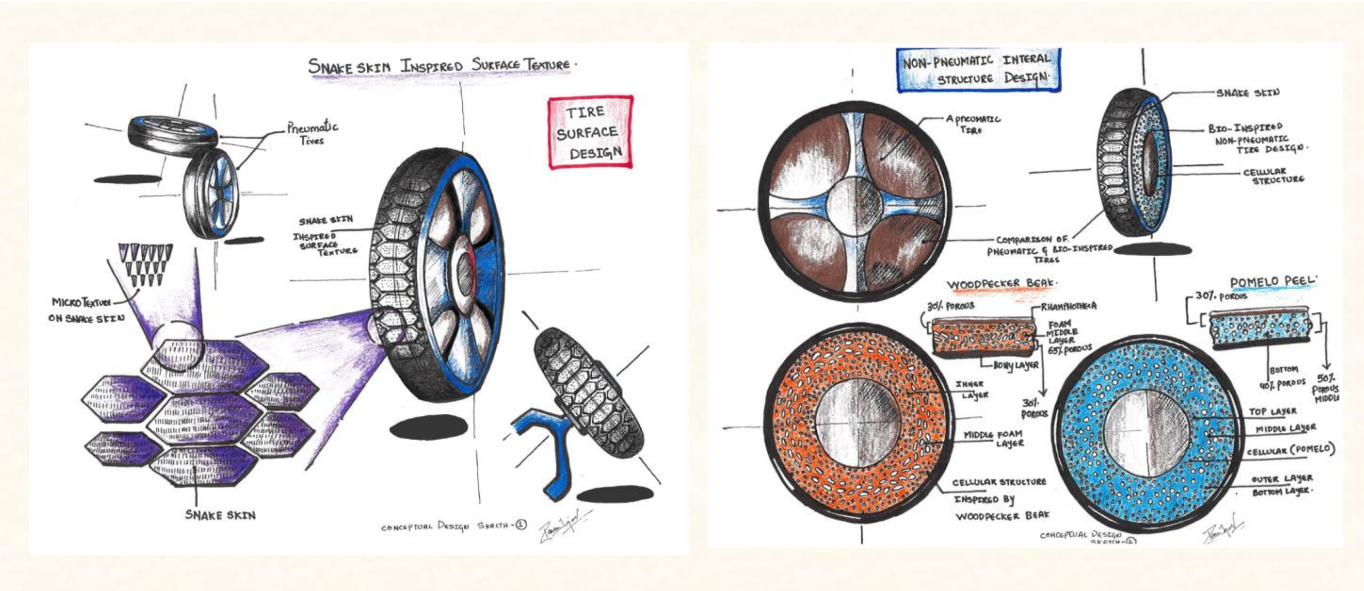

Figure 21. Multifunctional non-pneumatic tire design inspired by snake scales, the woodpecker's beak, and pomelo peel [69].

The design generation of this structure involved the following sequence:

(a) *Classification:* Figure 22 shows that snake scales with biological features characteristic of body/skin texture are classified as belonging to the surface domain. Figure 23 shows the mapping of the snake scales to their respective tissue. Similarly, Figure 24 shows the woodpecker's foamy beak, with biological features characteristic of stochastic tessellation, is classified as belonging to the cellular-structure domain. Figure 25 shows the mapping of the woodpecker's beak to its respective tissue. As shown in Figure 26, pomelo peel with biological features characteristic of stochastic tessellation is classified as a cellular structure.

(b) *Mapping:* The classified biological features are mapped to the respective tissues from which they originate. The snake scales are mapped to the epidermis tissue containing keratin proteins [38]. Similarly, the foamy layer of the woodpecker's beak is an inner bone layer, and is mapped to the connective tissue [47]. Likewise, the pomelo peel's stochastic structure is denoted by the formation of vascular bundles by the parenchymatic tissue [46]. Figure 23 shows the materials of the tissue from which the biological feature is made. Mapping initiates and ensures the search for appropriate material selection for the new design that matches the properties of biological materials. As shown, the scale of a snake arises due to keratin layers. Similarly, as shown in Figure 25, the foamy layer is formed by bundles of collagen fibers [70]. Figure 27 shows that vascular bundles are made up of xylem and phloem (sieve tubes) [44]. For this study, structural analysis was performed to compare the deformation between the woodpecker's foam and the pomelo peel's foam, and the material aspect was omitted.

(c) *Representation:* Figures 25 and 27 show the embodiment function of the snake scales to manage friction is represented as a combination of the integrated structure that is microstructure (triangular) on the central ventral and side ventral scales and the structural strategy is the arrangement of the scales in caudal elevation [71]. Similarly, the woodpecker's beak embodiment function (to absorb impact) is represented as a combination of the integrated structure that is the gradient foamy stochastic tessellations, and the structural strategy is the stochasticity of the foam [72]. Likewise, the embodiment function of the pomelo peel (to absorb impact) is represented as the combination of the integrated structure which is the porous structure and the structural strategy which is the arrangement of dense vascular bundles in a stochastic manner [46].

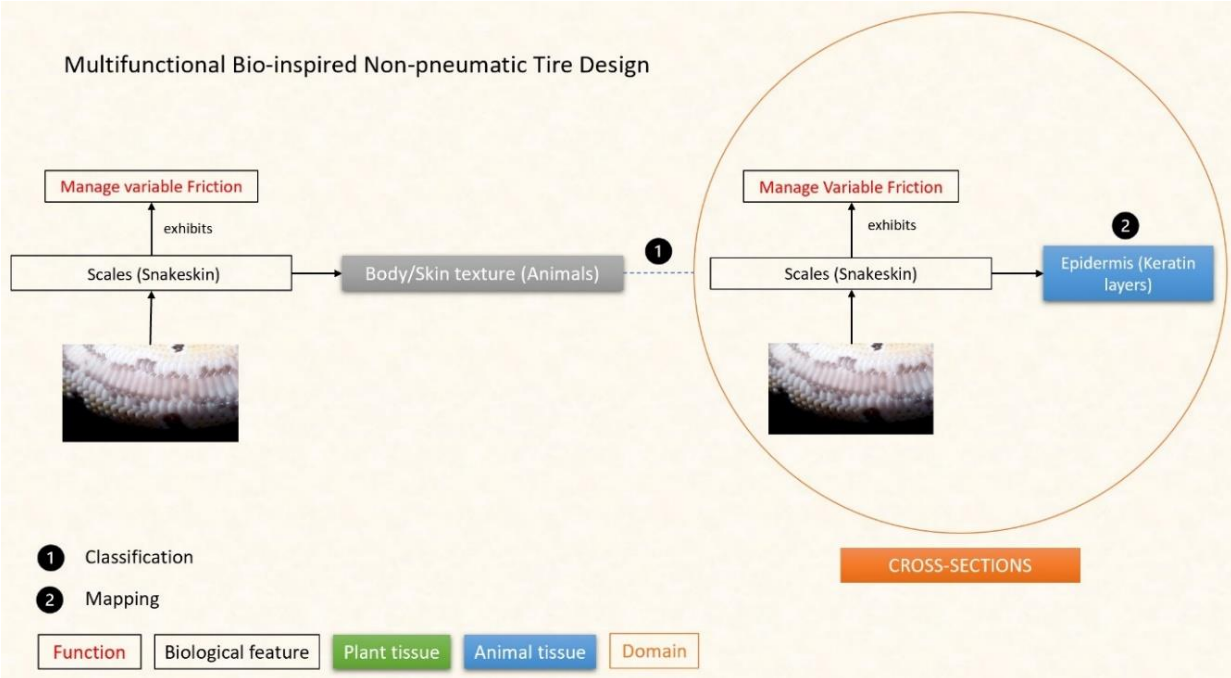

Figure 22. Classification and mapping of the snakeskin to its respective domain and the respective tissue from which it originated.

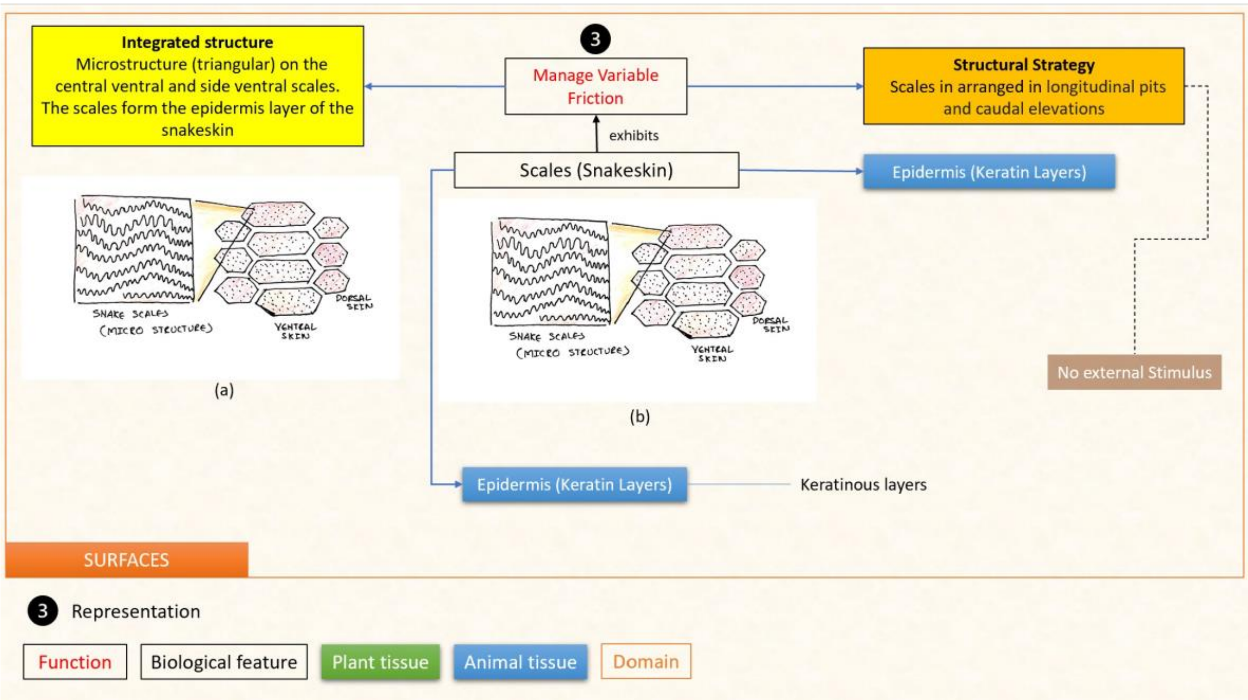

Figure 23. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**,**b**) [41].

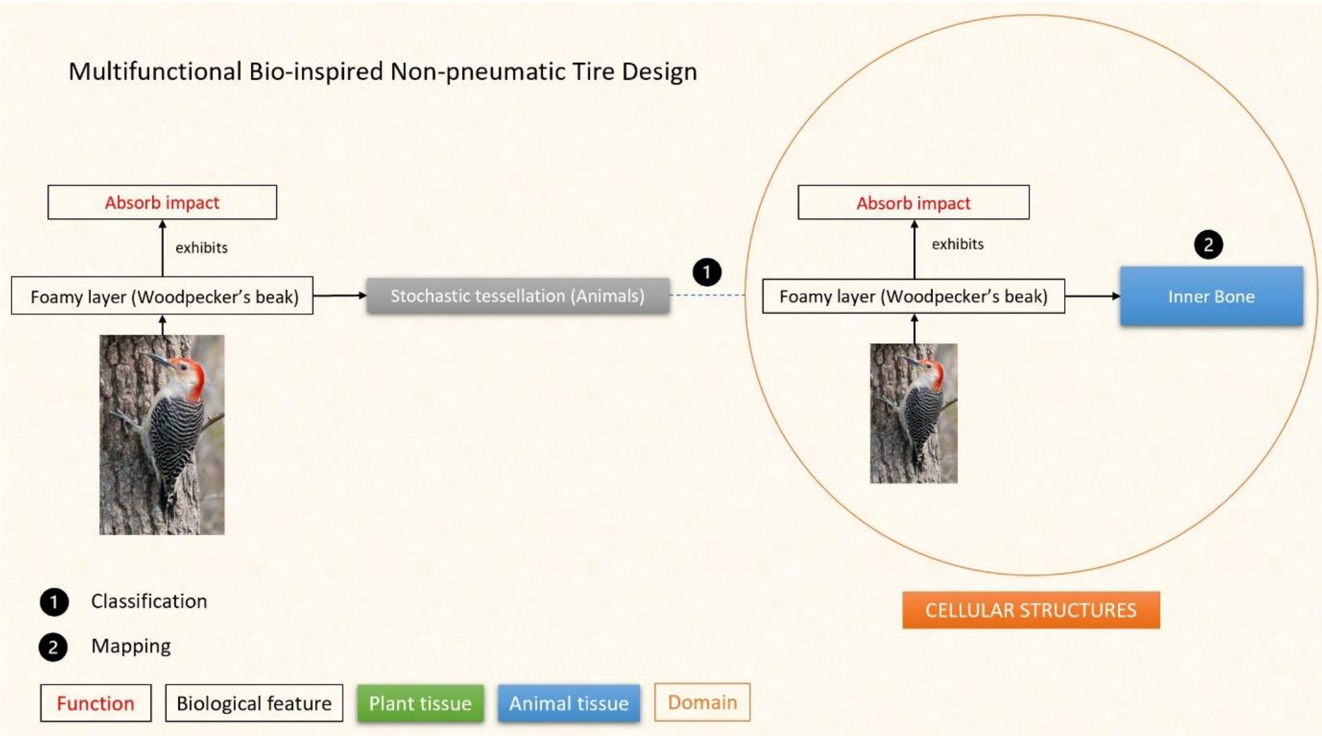

Figure 24. Classification and mapping of the woodpecker's beak (foam) to its respective domain and to the respective tissue from which it originated.

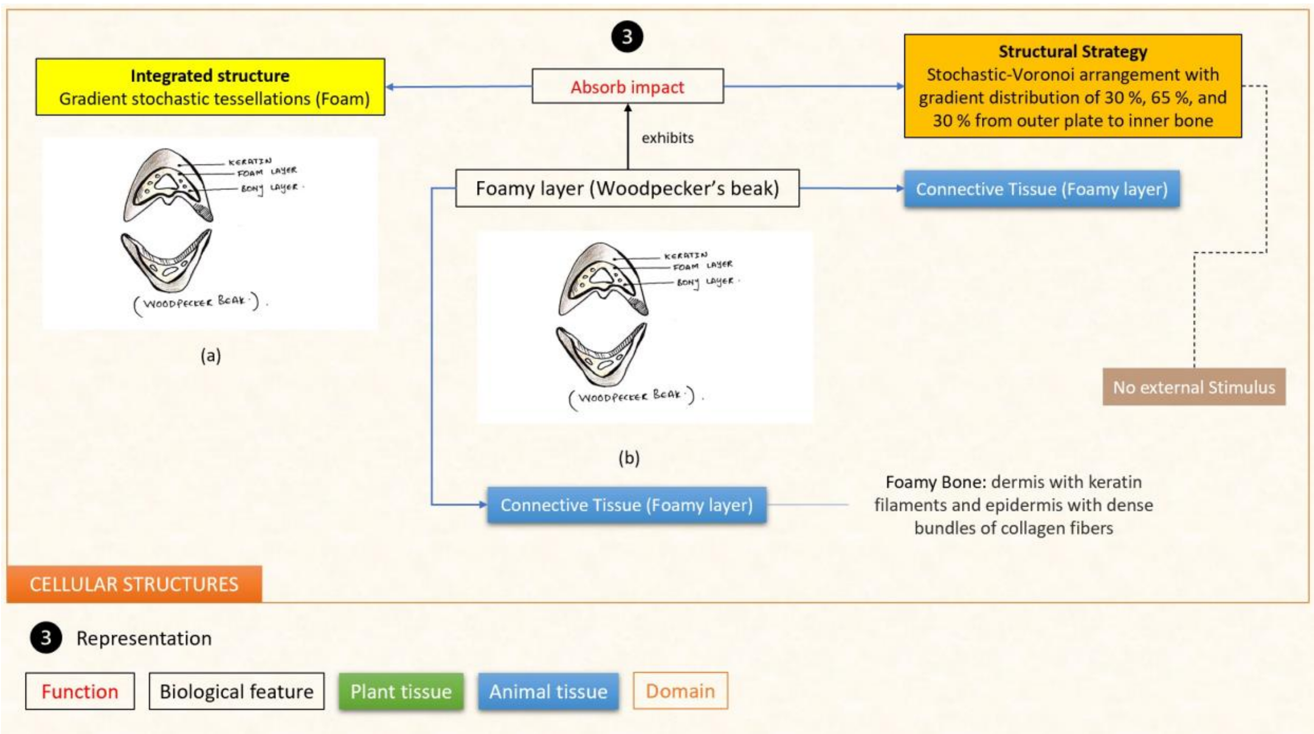

Figure 25. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**) and (**b**) [73].

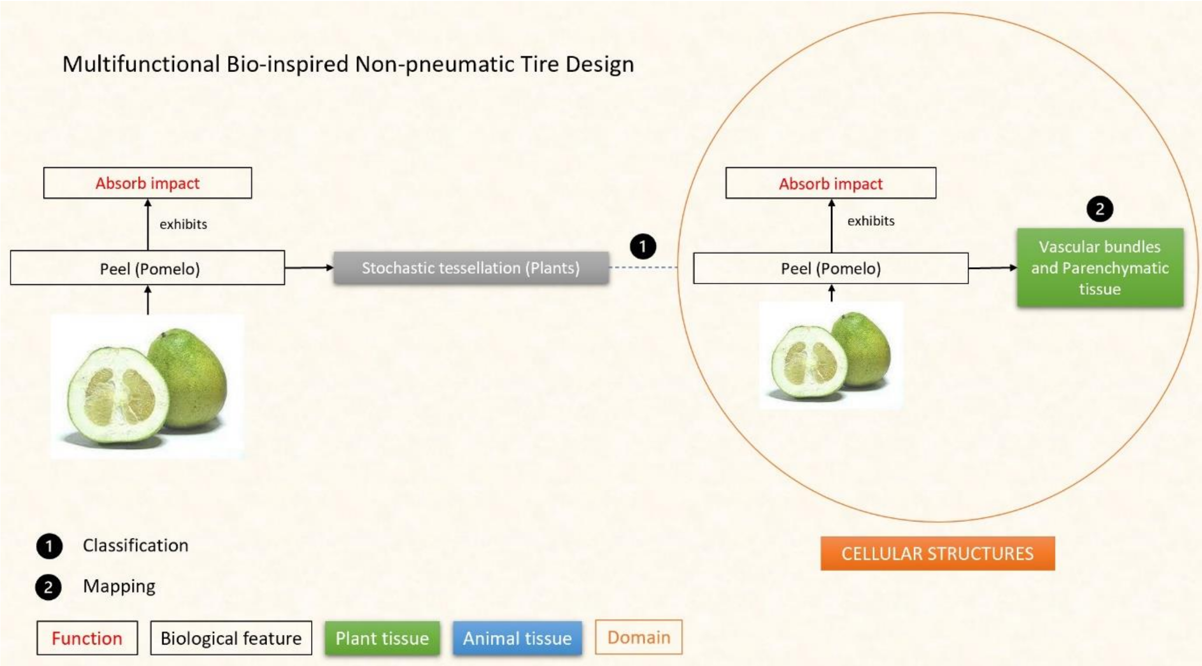

Figure 26. Classification and mapping of the pomelo peel (foam) to its domain and to the respective tissue from which it originated.

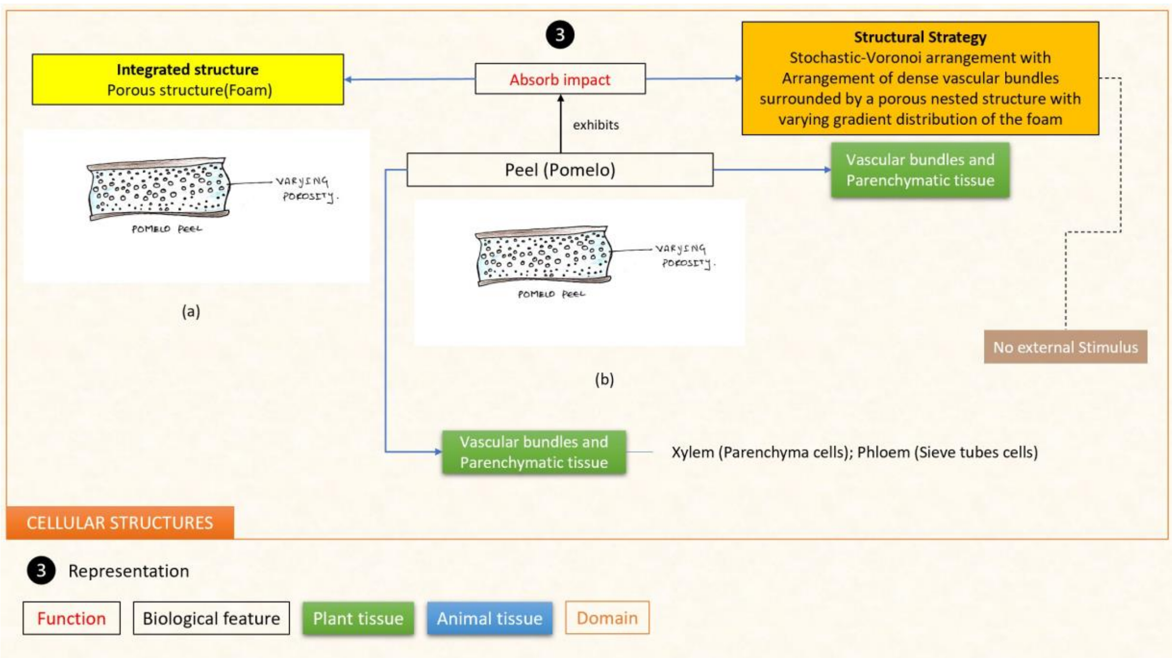

Figure 27. Representation of the function as a combination of integrated structure and the structural strategy. Picture inspiration (**a**) and (**b**) [74].

The final multifunctional design was obtained as a combination of the snakeskin scales structure and the foamy layers of the woodpecker's beak and pomelo peel.

5. Conclusions

This paper presented a detailed case-based classification, mapping, and representation of the xDID model, which aims to support the creation of distinctive and unique multifunctional conceptual designs. The biological features classified were taken from the reported bio-inspired design case studies in the literature. The previously defined DID approach is based on the classification of biological features and their tissues into various geometric designations called domains. The shapes and cross-sections were considered sub-domains for only the cellular structures domain. However, in the vast biological world, it is observed that certain biological features are complex, and this makes the classification based on definitions of domains in DID quite strenuous. To accommodate the classification of complex features, the xDID model is proposed. Furthermore, the high complexity of biological features makes it tough to classify them into a finite set of domains. The proposed xDID model is an extension of the previously defined DID method that facilitates the creation of new domains for the biological features that cannot be described by any of the current definitions of domains. The xDID model consists of three steps: classification, mapping, and representation. It was developed to enhance the rapidity of ideation and development of multifunctional bio-inspired concepts. The xDID model provides a unique approach to creating a common platform for effective collaboration for biologists, designers, and engineers by mapping biological features to their respective biological tissues. This mapping enhances the understanding and application of the structural and material aspects of the biological features. In a multidisciplinary team of designers, biologists, and engineers, classification, mapping, and representation enhances the emulation and development of bio-inspired products through understanding the biological feature's mechanisms as well as their structural and material aspects.

The xDID model is the first of its kind to classify biological features into their respective geometric designations (domains) and map them to their tissue of origin. The aim of such an approach is for agile ideation and innovation to design and develop multifunctional and multiscale conceptual designs by reducing the gap between biology, engineering, and design. For example, designers can quickly select features in surface domains and integrate features within other domains for rapid innovation of multifunctional products.

The major difference between the other multifunctional BID methods and the xDID model is that most of the other methods were developed from the functional decomposition approach and represent the entire biological system using functional modeling. These methods do not classify and map functional biological features. The xDID model on the other hand was developed based on a unique approach of classifying functional biological features according to their geometric designation and mapping them to the tissue of its origin. The xDID model was built to accommodate all functional biological features observed in the animal and plant kingdoms without any limitations on the type of species. For example, functional biological features from mammals, vertebrates, invertebrates, etc., can be classified, mapped, and represented using the xDID model.

The xDID model was primarily built as a problem-driven BID. However, as the knowledge database of the xDID model expands, there may be solutions that can be developed for problems that were not foreseen. However, classifying and mapping the observed functional biological features will be difficult to achieve. Biological features are complex, and classification based on the current descriptions of the domains is hard. Furthermore, certain biological features are highly complex and require the creation of new domains (geometric designations) for their classification. Nevertheless, the xDID model is a first step towards an agile innovation process using multifunctional BID.

Expanding the knowledge database of the xDID model requires collaboration between biologists, designers, and engineers. An inter-rater agreement might not be necessary as the classification can often be verified by involving biologists.

In this research, the application of the xDID model is validated through three multifunctional bio-inspired case studies. The next steps of the research will involve presenting the developed knowledge database and defining the meta-level parameters to filter the relevant biological analogies under convergent evolution. Convergent evolution is where distant biological features exhibit the same functions in radically different ways.

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References

1. Guadarrama-Cetina, J.; Mongruel, A.; Medici, M.-G.; Baquero, E.; Parker, A.; Milimouk-Melnytchuk, I.; González-Viñas, W.; Beysens, D. Dew condensation on desert beetle skin. *Eur. Phys. J. E* **2014**, *37*, 109. [CrossRef]
2. San Ha, N.; Lu, G. A review of recent research on bio-inspired structures and materials for energy absorption applications. *Compos. Part B Eng.* **2020**, *181*, 107496.
3. Vattam, S.; Wiltgen, B.; Helms, M.; Goel, A.; Yen, J. Fostering Creativity in and through Biologically Inspired Design. In *Design Creativity 2010*; Springer: Dane, WI, USA, 2011.
4. Helms, M.; Vattam, S.S.; Goel, A.K. Biologically inspired design: Process and products. *Des. Stud.* **2009**, *30*, 606–622. [CrossRef]
5. Ceschin, F.; Gaziulusoy, I. Evolution of design for sustainability: From product design to design for system innovations and transitions. *Des. Stud.* **2016**, *47*, 118–163. [CrossRef]
6. Goel, A.K.; Bras, B.; Helms, M.; Rugaber, S.; Tovey, C.; Vattam, S.; Weissburg, M.; Wiltgen, B.; Yen, J. Design patterns and cross-domain analogies in biologically inspired sustainable design. In Proceedings of the 2011 AAAI Spring Symposium Series, Stanford, CA, USA, 21–23 March 2011.
7. Fish, F.E.; Beneski, J.T. Evolution and bio-inspired design: Natural limitations. In *Biologically Inspired Design*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 287–312.
8. Ren, L.; Liang, Y. Biological couplings: Classification and characteristic rules. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 2791–2800. [CrossRef]
9. Ren, L.; Liang, Y. Biological couplings: Function, characteristics and implementation mode. *Sci. China Technol. Sci.* **2010**, *53*, 379–387. [CrossRef]
10. Du Plessis, A.; Broeckhoven, C.; Yadroitsava, I.; Yadroitsev, I.; Hands, C.H.; Kunju, R.; Bhate, D. Beautiful and functional: A review of biomimetic design in additive manufacturing. *Addit. Manuf.* **2019**, *27*, 408–427. [CrossRef]
11. Chen, P.-Y.; McKittrick, J.; Meyers, M.A. Biological materials: Functional adaptations and bioinspired designs. *Prog. Mater. Sci.* **2012**, *57*, 1492–1704. [CrossRef]
12. Han, Z.; Mu, Z.; Yin, W.; Li, W.; Niu, S.; Zhang, J.; Ren, L. Biomimetic multifunctional surfaces inspired from animals. *Adv. Colloid Interface Sci.* **2016**, *234*, 27–50. [CrossRef]
13. Zhang, M.; Feng, S.; Wang, L.; Zheng, Y. Lotus effect in wetting and self-cleaning. *Biotribology* **2016**, *5*, 31–43. [CrossRef]
14. Bhate, D.; Penick, C.A.; Ferry, L.A.; Lee, C. Classification and selection of cellular materials in mechanical design: Engineering and biomimetic approaches. *Designs* **2019**, *3*, 19. [CrossRef]
15. Badarnah, L.; Kadri, U. A methodology for the generation of biomimetic design concepts. *Archit. Sci. Rev.* **2015**, *58*, 120–133. [CrossRef]
16. Bhasin, D.; McAdams, D.A.; Layton, A. A product architecture-based tool for bioinspired function-sharing. *J. Mech. Des.* **2021**, *143*, 081401. [CrossRef]
17. Altshuller, G.; Al'tov, G.; Altov, H. *And Suddenly the Inventor Appeared: Triz, the Theory of Inventive Problem Solving*; Technical Innovation Center, Inc.: Worcester, MA, USA, 1996.
18. Svendsen, N.W.; Lenau, T.A. Approaches to analyzing multi-functional problems. In Proceedings of the DS 101: Proceedings of NordDesign 2020, Lyngby, Denmark, 12–14 August 2020; pp. 1–12.
19. Tan, R.; Liu, W.; Cao, G.; Shi, Y. Creative design inspired by biological knowledge: Technologies and methods. *Front. Mech. Eng.* **2019**, *14*, 1–14. [CrossRef]
20. Zhang, P.; Li, X.; Nie, Z.; Yu, F.; Liu, W. A Trimming Design Method Based on Bio-Inspired Design for System Innovation. *Appl. Sci.* **2021**, *11*, 4060. [CrossRef]
21. Tan, N.; Sun, Z.; Mohan, R.E.; Brahmananthan, N.; Venkataraman, S.; Sosa, R.; Wood, K. A system-of-systems bio-inspired design process: Conceptual design and physical prototype of a reconfigurable robot capable of multi-modal locomotion. *Front. Neurorobot.* **2019**, *13*, 78. [CrossRef]
22. Vattam, S.S.; Helms, M.E.; Goel, A.K. Compound analogical design: Interaction between problem decomposition and analogical transfer in biologically inspired design. In *Design Computing and Cognition'08*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 377–396.
23. Velivela, P.T.; Zhao, Y.F. A Comparative Analysis of the State-of-the-Art Methods for Multifunctional Bio-Inspired Design and an Introduction to Domain Integrated Design (DID). *Designs* **2022**, *6*, 120. [CrossRef]
24. Velivela, P.T.; Letov, N.; Liu, Y.; Zhao, Y.F. Application of Domain Integrated Design Methodology for Bio-Inspired Design-A Case Study of Suture Pin Design. *Proc. Des. Soc.* **2021**, *1*, 487–496. [CrossRef]

25. Liu, Z.; Jiao, D.; Weng, Z.; Zhang, Z. Structure and mechanical behaviors of protective armored pangolin scales and effects of hydration and orientation. *J. Mech. Behav. Biomed. Mater.* **2016**, *56*, 165–174. [CrossRef]
26. Ingrole, A.; Aguirre, T.G.; Fuller, L.; Donahue, S.W. Bioinspired energy absorbing material designs using additive manufacturing. *J. Mech. Behav. Biomed. Mater.* **2021**, *119*, 104518. [CrossRef]
27. Chowdhury, H.; Islam, R.; Hussein, M.; Zaid, M.; Loganathan, B.; Alam, F. Design of an energy efficient car by biomimicry of a boxfish. *Energy Procedia* **2019**, *160*, 40–44. [CrossRef]
28. McKeag, T. Auspicious Designs. In *Zygote Quarterly Summer 2012*; ISSUU: Palo Alto, CA, USA, 2012; ISSN 1927-8314.
29. Ezemba, J.; Layton, A. Bio-Inspired Avenues for Advancing Brain Injury Prevention. *J. Mech. Des.* **2022**, *144*, 121403. [CrossRef]
30. Seki, Y.; Bodde, S.G.; Meyers, M.A. Toucan and hornbill beaks: A comparative study. *Acta Biomater.* **2010**, *6*, 331–343. [CrossRef]
31. Marshall, W.F. Origins of cellular geometry. *BMC Biol.* **2011**, *9*, 57. [CrossRef]
32. Langille, R. Human Tissues and Systems. *NSCC Hum. Biol.* **2020**, *3*, 32–34.
33. Crang, R.; Lyons-Sobaski, S.; Wise, R. Parenchyma, collenchyma, and sclerenchyma. In *Plant Anatomy*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 181–213.
34. Rogers, A.W. *Cells and Tissues*; Academic Press: London, UK; New York, NY, USA, 1983.
35. Willocx, M.; Duflou, J. Combining bio-inspiration and ecodesign. *Procedia CIRP* **2021**, *98*, 595–600. [CrossRef]
36. Habib, M.K.; Nagata, F. Bioinspired design: Creativity and sustainability. In Proceedings of the 2019 20th International Conference on Research and Education in Mechatronics (REM), Wels, Austria, 23–24 May 2019; pp. 1–5.
37. Ensikat, H.J.; Ditsche-Kuru, P.; Neinhuis, C.; Barthlott, W. Superhydrophobicity in perfection: The outstanding properties of the lotus leaf. *Beilstein J. Nanotechnol.* **2011**, *2*, 152–161. [CrossRef]
38. Wang, B.; Yang, W.; McKittrick, J.; Meyers, M.A. Keratin: Structure, mechanical properties, occurrence in biological organisms, and efforts at bioinspiration. *Prog. Mater. Sci.* **2016**, *76*, 229–318. [CrossRef]
39. Seki, Y. *Structure and Mechanical Behavior of Bird Beaks*; University of California: San Diego, CA, USA, 2009.
40. Luo, Y.; Yuan, L.; Li, J.; Wang, J. Boundary layer drag reduction research hypotheses derived from bio-inspired surface and recent advanced applications. *Micron* **2015**, *79*, 59–73. [CrossRef] [PubMed]
41. Tiner, C.; Bapat, S.; Nath, S.D.; Atre, S.V.; Malshe, A. Exploring convergence of snake-skin-inspired texture designs and additive manufacturing for mechanical traction. *Procedia Manuf.* **2019**, *34*, 640–646. [CrossRef]
42. Wilt, F.H.; Killian, C.E.; Livingston, B.T. Development of calcareous skeletal elements in invertebrates. *Differ. Rev.* **2003**, *71*, 237–250. [CrossRef]
43. Alibardi, L. Cell biology of adhesive setae in gecko lizards. *Zoology* **2009**, *112*, 403–424. [CrossRef] [PubMed]
44. Jung, J.H.; Park, C.M. Vascular development in plants: Specification of xylem and phloem tissues. *J. Plant Biol.* **2007**, *50*, 301–305. [CrossRef]
45. Zhang, W.; Yin, S.; Yu, T.; Xu, J. Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb. *Int. J. Impact Eng.* **2019**, *125*, 163–172. [CrossRef]
46. Bührig-Polaczek, A.; Fleck, C.; Speck, T.; Schüler, P.; Fischer, S.; Caliaro, M.; Thielen, M. Biomimetic cellular metals—Using hierarchical structuring for energy absorption. *Bioinspir. Biomim.* **2016**, *11*, 045002. [CrossRef]
47. Rico-Guevara, A.; Sustaita, D.; Gussekloo, S.; Olsen, A.; Bright, J.; Corbin, C.; Dudley, R. Feeding in birds: Thriving in terrestrial, aquatic, and aerial niches. In *Feeding in Vertebrates*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 643–693.
48. Trotta, M.G. Bio-inspired design methodology. *Int. J. Inf. Sci.* **2011**, *1*, 1–11. [CrossRef]
49. Helfman Cohen, Y.; Reich, Y.; Greenberg, S. Biomimetics: Structure–function patterns approach. *J. Mech. Des.* **2014**, *136*, 111108. [CrossRef]
50. Yu, C.; Liu, M.; Zhang, C.; Yan, H.; Zhang, M.; Wu, Q.; Liu, M.; Jiang, L. Bio-inspired drag reduction: From nature organisms to artificial functional surfaces. *Giant* **2020**, *2*, 100017. [CrossRef]
51. Lienhard, J.; Schleicher, S.; Knippers, J. Bio-inspired, flexible structures and materials. In *Biotechnologies and Biomimetics for Civil Engineering*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 275–296.
52. Gao, X. Antifogging Properties in Mosquito Eyes. In *Encyclopedia of Nanotechnology*; Bhushan, B., Ed.; Springer: Dordrecht, The Netherlands, 2012; pp. 117–121. [CrossRef]
53. Deng, Y.-M.; Britton, G.; Tor, S. A design perspective of mechanical function and its object-oriented representation scheme. *Eng. Comput.* **1998**, *14*, 309–320. [CrossRef]
54. Keshwani, S.; Chakrabarti, A. Towards automatic classification of description of analogies into SAPPhIRE constructs. In *Research into Design for Communities, Proceedings of ICoRD 2017, Guwahati, India, 9–11 January 2017*; Springer: Singapore, 2017; Volume 2, pp. 643–655.
55. Goel, A.K.; Rugaber, S.; Vattam, S. Structure, behavior, and function of complex systems: The structure, behavior, and function modeling language. *Ai Edam* **2009**, *23*, 23–35. [CrossRef]
56. Zhang, W.; Tor, S.B.; Britton, G.; Deng, Y. Functional Design of Mechanical Products Based on Behavior-Driven Function-Environment-Structure Modeling Framework. 2002. Available online: https://dspace.mit.edu/handle/1721.1/4031 (accessed on 15 April 2023).
57. Cowan, F.S.; Allen, J.K.; Mistree, F. Functional modelling in engineering design: A perspectival approach featuring living systems theory. *Syst. Res. Behav. Sci. Off. J. Int. Fed. Syst. Res.* **2006**, *23*, 365–381. [CrossRef]

58. Han, Z.; Zhu, B.; Yang, M.; Niu, S.; Song, H.; Zhang, J. The effect of the micro-structures on the scorpion surface for improving the anti-erosion performance. *Surf. Coat. Technol.* **2017**, *313*, 143–150. [CrossRef]
59. Chou, S.; Overfelt, R. Tensile deformation and failure of North American porcupine quills. *Mater. Sci. Eng. C* **2011**, *31*, 1729–1736. [CrossRef]
60. Koons, G.L.; Diba, M.; Mikos, A.G. Materials design for bone-tissue engineering. *Nat. Rev. Mater.* **2020**, *5*, 584–603. [CrossRef]
61. Karp, J.M. Porcupine-Inspired Needles. 2014. Available online: https://www.karplab.net/portfolio-item/porcupine-inspired-needles (accessed on 2 July 2020).
62. Crandell, K.; Howe, R.; Falkingham, P. Repeated evolution of drag reduction at the air–water interface in diving kingfishers. *J. R. Soc. Interface* **2019**, *16*, 20190125. [CrossRef]
63. Shivangi Sarabhai, P.T.V.; Zhao, Y.F.; Sanchez, F.; Kibsey, M. Comparative study of the flow and heat characteristics of non-stochastic lattice and bio-inspired multi-scale structures for gas turbine engine applications. In Proceedings of the ASME Turbo Expo 2023 Turbomachinery Technical Conference and Exposition (GT2023), Boston, MA, USA, 26–30 June 2023.
64. Alsafy, M.A.; El-gendy, S.A.; Abumandour, M.M. Computed tomography and gross anatomical studies on the head of one-humped camel (Camelus dromedarius). *Anat. Rec.* **2014**, *297*, 630–642. [CrossRef]
65. Parvizi, J. *High Yield Orthopaedics E-Book*; Elsevier Health Sciences: Amsterdam, The Netherlands, 2010.
66. Shahda, M.M.; Abd Elhafeez, M.M.; El Mokadem, A.A. Camel's nose strategy: New innovative architectural application for desert buildings. *Sol. Energy* **2018**, *176*, 725–741. [CrossRef]
67. Sun, J.; Bhushan, B. Structure and mechanical properties of beetle wings: A review. *Rsc Adv.* **2012**, *2*, 12606–12623. [CrossRef]
68. Abbas, A.; Zhang, C.; Asad, M.; Waqas, A.; Khatoon, A.; Hussain, S.; Mir, S.H. Recent developments in artificial super-wettable surfaces based on bioinspired polymeric materials for biomedical applications. *Polymers* **2022**, *14*, 238. [CrossRef]
69. Velivela, P.; Letov, N.; Kong, L.; Zhao, Y. A case study of multifunctional non-pneumatic tire design for the validation of meta-level design parameter in domain integrated design (did) metHOD. *Proc. Design Soc.* **2023**, *3*, 39–48. [CrossRef]
70. Zhang, W.; Xu, J.; Yu, T. Dynamic behaviors of bio-inspired structures: Design, mechanisms, and models. *Eng. Struct.* **2022**, *265*, 114490. [CrossRef]
71. Klein, M.-C.G.; Gorb, S.N. Epidermis architecture and material properties of the skin of four snake species. *J. R. Soc. Interface* **2012**, *9*, 3140–3155. [CrossRef]
72. Wang, L.; Lu, S.; Liu, X.; Niu, X.; Wang, C.; Ni, Y.; Zhao, M.; Feng, C.; Zhang, M.; Fan, Y. Biomechanism of impact resistance in the woodpecker's head and its application. *Sci. China Life Sci.* **2013**, *56*, 715–719. [CrossRef] [PubMed]
73. Lee, N.; Horstemeyer, M.; Rhee, H.; Nabors, B.; Liao, J.; Williams, L.N. Hierarchical multiscale structure–property relationships of the red-bellied woodpecker (*Melanerpes carolinus*) beak. *J. R. Soc. Interface* **2014**, *11*, 20140274. [CrossRef] [PubMed]
74. Yang, B.; Chen, W.; Xin, R.; Zhou, X.; Tan, D.; Ding, C.; Wu, Y.; Yin, L.; Chen, C.; Wang, S. Pomelo peel-inspired 3D-printed porous structure for efficient absorption of compressive strain energy. *J. Bionic Eng.* **2022**, *19*, 448–457. [CrossRef]