Multifunctional Bio-inspired Design (MBID)

A rapid idea generation system for multifunctional bio-inspired designs

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Abstract

Bio-inspired design, Bioinspiration, or Biomimetics refers to designing concepts by drawing inspiration from nature or biological systems to create products, systems, or structures that solve multiple functions or purposes. This approach involves mimicking either the strategy, efficiency, adaptability, or other evolving advantageous features found in nature. An example of such an approach is the design of a robotic surgical device that can navigate between tissues, which is inspired by the flexibility and dexterity of an elephant's trunk. This research aims to investigate the multifunctional design concept generation and develop a rapid idea-generation system that can harness the innovative solutions that have evolved in natural systems over millions of years to address the complex challenges in engineering and design. However, current state-of-the-art methods and tools for bio-inspired design were developed to mimic only one functional feature. Only a few methods were developed that can support the generation of multifunctional conceptual designs. Growing human needs and environmental challenges necessitate creative solutions, like the need for sustainable multifunctional products to minimize environmental impact and innovative approaches to address complex engineering issues. Bioinspiration serves as a valuable source for generating multifunctional innovative solutions to these challenges. A gap still exists in the multifunctional design concept generation field and its corresponding idea-generation system that supports the rapid creation of multifunctional conceptual and early-stage embodiment designs. This research proposes a novel abstraction, classification, and mapping method of biological features and is implemented as a rapid idea-generation system that starts with the abstraction of biological features, which involves representing the biological feature at the embodiment level function as a combination of its physical structure and structural strategy. This approach simplifies the current complex system-level abstraction of biological features. The next step involves the classification and mapping of biological features based on their feature

characteristics into their respective geometric designations called Domains. Integration of the biological features from these Domains results in the generation of multifunctional bio-inspired conceptual and early-stage embodiment designs. Classification and mapping enable the rapid and appropriate selection of biological features based on structure, geometric relevance, and function. In addition, the classified biological features are mapped to their respective tissues from which they originate. It initiates and ensures the search for appropriate material selection for the new design that matches the properties of biological materials in the subsequent detailed design stages. Moreover, in nature, different biological organisms exhibit similar functions with different biological features. To select the most relevant features for inspiration/mimicry from those that exhibit the same function and have a similar geometric relevance, specific quantitative criteria have been proposed.

The output of the rapid idea-generation system is the generation of novel bio-inspired designs. Several case studies have been carried out to validate the effectiveness of this method and system such as bio-inspired multifunctional painless sutures leg/pin design, bio-inspired multifunctional non-pneumatic tire design, and bio-inspired effective heat transfer with low-pressure drop structures for aerospace applications.

Résumé

Le design bio-inspiré, la bioinspiration ou la biomimétique désigne le design conceptuel en s'inspirant de la nature ou des systèmes biologiques pour créer des produits, des systèmes ou des structures qui résolvent plusieurs fonctions ou objectifs. Cette approche implique de reproduire la stratégie, l'efficacité, l'adaptabilité ou d'autres caractéristiques évolutives avantageuses trouvées dans la nature. Un exemple de cette approche est la conception d'un dispositif chirurgical robotique capable de naviguer entre les tissus, inspiré par la flexibilité et la dextérité de la trompe d'un éléphant. L'objectif de cette recherche est d'explorer la génération de designs conceptuels multifonctionnels et de développer un système rapide de génération d'idées capable d'exploiter les solutions innovantes issues de millions d'années d'évolution dans les systèmes naturels pour résoudre les défis complexes en ingénierie et en design. Cependant, les méthodes et outils actuels de conception bio-inspirée ont été développés pour imiter seulement une fonctionnalité. Seules quelques méthodes ont été développées pour soutenir la générationde designs conceptuels multifonctionnels. Les besoins croissants de l'Homme et les défis environnementaux exigent des solutions créatives, comme la nécessité de produits durables et multifonctionnels pour minimiser l'impact environnemental et des approches innovantes pour résoudre les problèmes d'ingénierie complexes. La bioinspiration constitue une source précieuse pour générer des solutions innovantes multifonctionnelles à ces défis. Cependant, il existe encore un écart dans le domaine de la génération de designs conceptuels multifonctionnels et de son système de génération d'idées correspondant qui soutient la création rapide de designs conceptuels et de premiers stades de prototypes multifonctionnels.

Cette recherche propose une nouvelle méthode d'abstraction, de classification et d'association des caractéristiques biologiques et est mise en œuvre comme un système rapide de génération d'idées qui commence par l'abstraction des caractéristiques biologiques, impliquant la représentation

de la caractéristique biologique au niveau de matériel en tant que combinaison de sa structure physique et de sa stratégie structurelle. Cette approche simplifie l'abstraction actuelle complexe des caractéristiques biologiques au niveau du système. La prochaine étape consiste à classer et à cartographier les caractéristiques biologiques en fonctions de leurs propriétés dans leurs catégories géométriques respectives appelées domaines. L'intégration des caractéristiques biologiques de ces domaines conduit à la génération designs conceptuels et de premiers stades de prototypes bio-inspirés multifonctionnels. La classification et l'association permettent la sélection rapide et appropriée des caractéristiques biologiques en fonction de la structure, de la pertinence géométrique et de la fonction. De plus, les caractéristiques biologiques classées sont associées à leurs tissus respectifs d'origine. Cela initie et garantit la recherche d'une sélection de matériaux appropriée pour la nouvelle conception correspondant aux propriétés des matériaux biologiques dans les étapes ultérieures de design détaillé. De plus, dans la nature, différents organismes biologiques présentent des fonctions similaires avec des caractéristiques biologiques différentes. Pour sélectionner les caractéristiques les plus pertinentes pour l'inspiration/l'imitation parmi celles qui présentent la même fonction et ont une pertinence géométrique similaire, des critères quantitatifs spécifiques ont été proposés.

Le produit du système rapide de génération d'idées est la génération designs bio-inspirés novateurs. Plusieurs études de cas ont été menées pour valider l'efficacité de cette méthode et de ce système, telles que la conception d'agrafes à suture bio-inspirées multifonctionnelles et indolores, roues bio-inspirées non-pneumatiques multifonctionnelles, le transfert de chaleur bio-inspiré efficace et des structures à faible perte de charge pour les applications aérospatiales.

Contributions

This research introduces a new rapid idea generation system for the generation of novel multifunctional bio-inspired conceptual and early-stage embodiment designs through an embodiment-level abstraction of the biological features (representation), accompanied by a geometric designation-based classification and mapping method of biological features, and a selection criteria for choosing relevant biological analogy. The following are the specifications of each component of the system:

- **Abstraction**: A novel representation technique illustrates functions exhibited through biological features by amalgamating their integrated structure with their structural strategy. This approach offers an abstraction at the embodiment level, simplifying the current complex system-level abstractions of biological features. At the embodiment function level, the function is directly linked to the physical structure. This approach is adaptable and can be seamlessly integrated into existing system-level representation techniques.

- **Acquisition and Simulacrum of biological features and their functions**: A knowledge database named *BIKAS: Bio-inspired Knowledge Acquisition and Simulacrum* is generated, encompassing biological features, their functions, integrated structures, and the structural strategies obtained through the analysis of bio-inspired design studies.

- **Classification and Mapping**: A novel method has been developed to classify biological features based on their characteristics, assigning them to specific geometric designations referred to as 'Domains.' These Domains include Surfaces, Cellular Structures, Cross-sections, and Shapes. The amalgamation of biological features from these Domains facilitates the creation of multifunctional conceptual and early-stage embodiment designs. Additionally, the categorized biological features are mapped to their originating tissues. This method is denoted as *Domain Integrated Design (DID).*

The **classification** allows for the swift and precise identification of biological characteristics by considering their geometry, configuration, and operational functionality.

The **mapping** enhances the understanding and application of the structural and material composition of the feature. It initiates and ensures the search for appropriate material selection for the new design that aligns with the properties of biological materials.

- **Selection of suitable or relevant biological feature for emulation**: A novel quantitative criterion has been developed to facilitate the selection among biological features that share similar geometric relevance, scale, and functional characteristics (for instance, choosing between two cellular structures exhibiting the same functionality). This criterion, named *Meta-level design parameters*, enables a quantitative evaluation to discern between such comparable biological features. The meta-level design parameters are verified by generating novel multifunctional biomimetic early embodiment stage design concepts and using computer simulations to validate the generated concepts. The multifunctional bio-inspired designs are as follows.
  - Bio-inspired multifunctional underwater skins (Advanced suits).
  - Bio-inspired multifunctional helmet design for protection against head injuries.
- **Extension of Classification and Mapping**: The extension of the DID method involves the incorporation of additional domains and the establishment of micro-domains within existing domains. This adaptation aims to accommodate complex biological features, providing more embodiment-level structural descriptions and classifications based on their characteristics. The expanded version of the method is titled *Expandable Domain Integrated Design (xDID).*
- **Applications**: Validation of the method and the parameters is performed by generation and simulation-based analysis of novel multifunctional bio-inspired conceptual and early-stage embodiment design case studies. The case studies are as follows

– Bio-inspired multifunctional painless sutures: pin/leg design.
– Bio-inspired multifunctional non-pneumatic tire design
– Bio-inspired effective heat transfer and low-pressure drop structures for aerospace applications.

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I extend a heartfelt appreciation to my roommate, Suvedh Jaywanth, and my friends Chandan, and Yeshwanth for their support throughout these years.

Lastly, I dedicate this thesis to the memory of ***Late. Shri Sistla Ramakrishna Rao garu***, whose words of encouragement I carry with me always. I also dedicate this to my late grandfather, *Sri Seshagiri Rao*, my grandmother *Janaki Damerla*, and my parents, *Kalidas Velivela and Nagamani Velivela*

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Acronyms

- **AI**: **A**rtificial **I**ntelligence
- **NLP**: **N**atural **L**anguage **P**rocessing
- **ML**: **M**achine **L**earning
- **BID**: **B**io **I**nspired **D**esign
- **DID**: **D**omian **I**ntegrated **D**esign
- **xDID**: **E**xpandable **B**io **I**nspired **D**esign
- **MBID**: **M**ultifunctional **B**io **I**nspired **D**esign
- **BIKAS**: **B**io **I**nspired **K**nowledge **A**cquisition and **S**imulacrum

Terminology

This research introduces a comprehensive rapid idea generation system for generating novel multifunctional bio-inspired conceptual and early-stage embodiment designs. Various terminologies were introduced in this research. The definitions of the introduced terminologies are as follows:

- **Biological features**: refer to the morphological and anatomical features observed in plant and animal kingdoms.
- **Biological feature characteristics**: refer to the feature's appearance, apparent form, or physical trait.
- **Domains**: Domains represent different biological features performing various functions, mapped to their tissues with a common geometric designation.
- **Embodiment function**: refer to the fundamental function related to the physical structure
- **Integrated Structure**: refer to the physical description of the multiscale structure (e.g., micro/nanostructure, macrostructure, and the presence of wax layers on the structure, etc.).
- **Structural Strategy**: refer to the integrated structural configuration (e.g., arrangement of the micro or nanostructure, packing of the micro or nanostructure, orientation of micro or 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.).

Publications

All publications on simulations for multifunctional bio-inspired design concepts were conducted in partnership with students from ADML (Additive Design and Manufacturing Laboratory) in the Department of Mechanical Engineering at McGill University. The simulations validating the meta-level design parameters in Chapter 5 were performed in collaboration with Arnaud Ridard and Nikita Letov. The multifunctional bio-inspired painless sutures case study was executed in cooperation with Nikita Letov and Yuan Li. Similarly, the multifunctional bio-inspired non-pneumatic tire design case study was undertaken with Nikita Letov and Lingchen Kong. The third case study on bio-inspired effective heat transfer and low-pressure drop structures was carried out in collaboration with Shivangi Sarabhai from ADML, along with Mitch Kibsey and Fabian Sanchez from Siemens Energy.

The publication on knowledge extraction methods for the support of DID was carried out in collaboration with Siyuan Sun. The review on geometric modeling of complex bio-inspired designs was carried out in collaboration with Nikita Letov.

Journals

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Part I

Bio-inspired Design (BID)

1

Introduction to BID

Nature is one of the sources of inspiration for designers, engineers, and scientists in developing innovative products. Nature inspires us with a wide range of innovative solutions for complex engineering problems. Bio-inspired design (BID) is an approach that uses biological systems and features to distill novel solutions for complicated engineering problems [26,27]. Ever-increasing human demands and environmental problems require innovative solutions. For example, sustainable products are required to reduce the overall environmental impact, and innovative solutions are required to tackle emerging complex engineering problems such as water treatment, waste management, etc. Bioinspiration is a source to provide innovative solutions to such problems.

Bioinspiration has led the way in providing innovative solutions by exploring the 3.8 billion evolutionary strategies employed by biological systems for their survival. Figure 1.1 shows examples of biological analogy and their corresponding biological functions such as the Namib desert beetle's ability to absorb water from the fog using its micro-bumps on its surface, Kingfisher's beak-inspired cross-section for the reduction of sonic boon and reduce the aerodynamic drag in the Shinkansen bullet train in Japan, the slippery surface of the pitcher plant is formed by the crescent-shaped micro-structures that aid in catching insects, mimicking soft structures for soft robotic applications, Sharkskin inspired microstructures for fluidic drag reduction, and lotus leaf inspired structures for superhydrophibic and self-cleaning surfaces. In addition, biological organisms offer innovative ideas for enhancing the performance of various functions such as snakeskin structure for effective friction management [21], Box-fish inspired structure for reduction of aerodynamic/fluidic drag [28], Honeycomb cellular structure for lightweight design [29], Dragonfly [24] and Beetles forewing [30] for high load bearing capacity and lightweight, mimicking natural network designs for optoelectronic applications [31], Diatom's corrugated for effective energy absorption [32], and Desert scorpion back for anti-erosion application [15].

Although research on bio-inspired design started well over two decades ago, there are many definitions used to describe this research field. The formal definitions of Bio-Inspired Design or Bioinspiration and their underlying terms provided by the International Standards Organisation (ISO) 18458 are discussed below. These definitions were also reported in a comprehensive survey done by Fayemi, P.-E et.al., [8] and Leanu et.al., [33].

- ***Biomimetics***: Interdisciplinary creative process between biology and technology, aiming at solving anthroposphere problems through abstraction, transfer, and application of knowledge through biological models.

- ***Biomimicry/Bio-mimesis***: Philosophy that takes up challenges related to resilience (Social, environmental, and economic ones), by being inspired by living organisms, particularly at an organizational level.

- ***Bionics***: Technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/ or mechanical equivalent.

In addition, the term ***Bioreplication*** is defined as a biological structure that is directly reproduced to realize at least one specific functionality [33]. From the definitions, all the terms fall under the umbrella term of bioinspiration. The intersection between certain terms aligns well with the other fields of study such as robotics, and eco-design. Figure 1.2 shows the Venn diagram of bio-inspiration and its related terms with their overlaps. Apart from the formal definitions, biomimicry can be applied at various levels for example mimicking a reptile's skin for effective friction management to mimicking

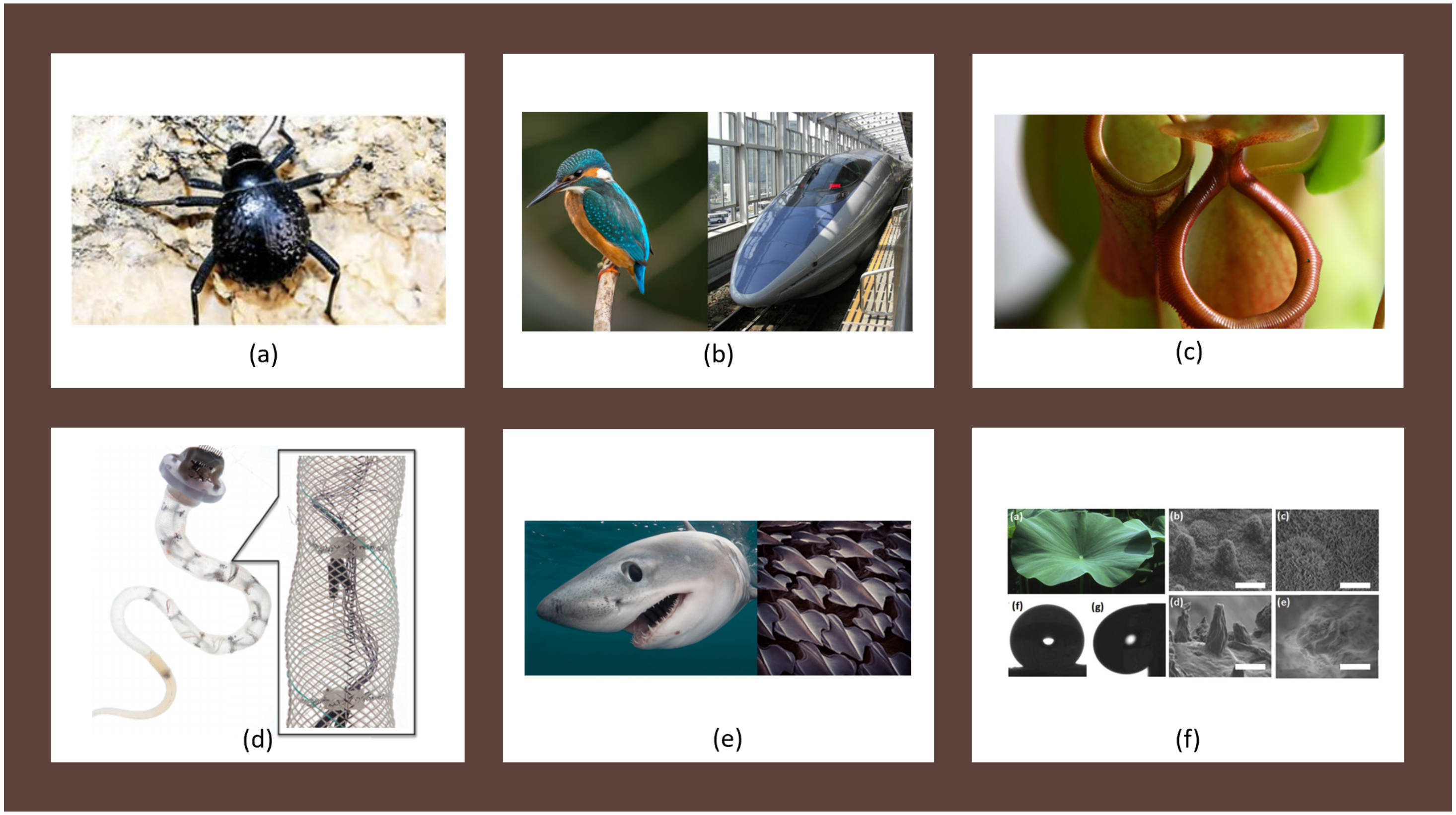

Figure 1.1: Schematic showing the examples of biological features exhibiting various functions such as a) Water absorption by Namib desert beetle's micro bumps on its surface [1]; b) Kingfisher beak inspired structure to reduce sonic boom in Shinkansen bullet train [2]; c) Slippery surfaces inspired from pitcher plant [3]; d) Mimicking soft structures for robotic application [4]; e) Sharkskin inspired structures for reduction of fluidic drag [5, 6]; f) Superhydrophobic Lotus leaf repel water and known for its self-cleaning property [7]

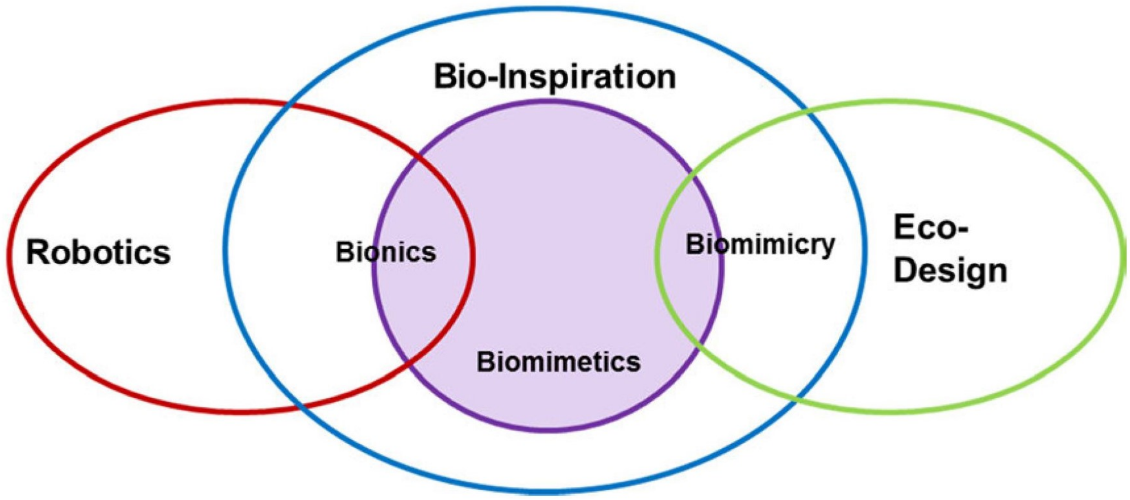

Figure 1.2: Bioinspiration and its related terms [8]

strategies inspired by biological systems for an organisation's performance improvement. Moreover, Fayemi, P.-E., et al. [8] discussed various levels at which biomimicry is applied. Case studies corresponding to each of the level was provided as an example. The following are the levels with their examples.

- ***Level 1***: Mimicking the form. As an example, the reduction in aerodynamic noise and sonic boom by redesigning the nose of the train and its pantograph by drawing inspiration from the beak of a Kingfisher, an Owl wings, and a Penguin's body, respectively.

- ***Level 2***: Mimicking of a natural process, where the focus is set on mimicking structures and functions. As an example, the replication of the gecko's hierarchical arrangement of microstructures called setae on its foot to produce gecko-inspired adhesive tapes.

- ***Level 3***: Mimicking the strategies of living. As an example, the design of the Eastgate centre that draws its inspiration from termite mounds that have a fascinating ability to maintain specific temperatures in a passive way.

The discussed terminologies and levels of biomimicry point out that the extracted biological strategy or bio-inspired principles can be applied at various levels from the generation of a solution to an engineering problem to the effective management strategy for an organization. In addition to the formal definitions and levels of biomimicry, there are two popular approaches defined for applying biomimicry.

Aziz, M.S. [9] discusses the popular top-down and bottom-up approaches associated with biomimicry. The definitions are as follows.

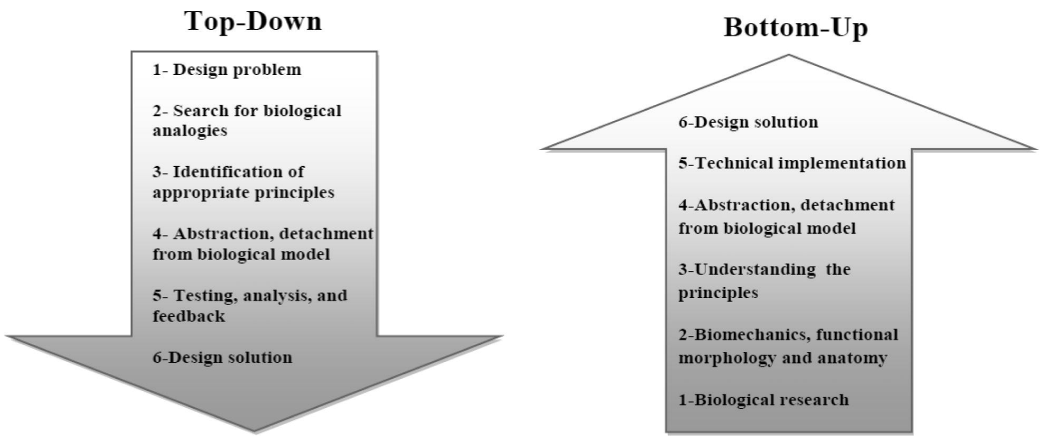

Figure 1.3: Top-Down and Botton-Up approaches [9]

- ***Problem driven or Top-Down approach***: In this approach, a technical problem can be solved by formulating a concise technical question for which evolution may have already developed an answer for.

- ***Solution driven or Bottom-Up approach***: In this approach, a biological functionality is discovered and then the functionality is used for a new design solution.

The Figure 1.3 shows the two approaches and the steps involved. However, the product development process contains various phases such as the concept phase, design phase, detailed design phase, and finally the qualification phase. All the critical decisions are taken at the conceptual design phase of the product development process to reduce the overall cost, time losses, etc. To leverage the principles of biological adaptations, various strategies, frameworks, methods, and tools were developed. The subsequent chapters of this thesis delve into a literature review encompassing the current state-of-the-art frameworks, methods, and tools. This is followed by an exploration of a novel idea-generation system crafted for generating multifunctional bio-inspired concepts and early-stage embodiment designs.

The utilization of immense functional structures in nature demands systematic and detailed frameworks, methods, and approaches. Biological and natural structures are inherently multifunctional. Nevertheless, replicating these structures to attain multifunctionality is not a straightforward process. It necessitates a methodical approach guiding designers to extract and comprehend the biological feature's function and subsequently redesign it to meet specific needs. Current state-of-the-art methods and tools mostly concentrate on emulating a single function. However, the escalating human needs and demands pose unforeseen complex engineering challenges, prompting the need for a rapid idea-generation system capable of producing multifunctional design concepts.

This research is dedicated to developing a rapid idea-generation system that facilitates abstraction, selection among biological features, and emulation of these features to achieve multifunctional conceptual and early-stage embodiment designs. This research provides a novel ideation system addressing the following objectives:

- Abstraction of the functions exhibited by biological features at the granular level, specifically at the embodiment level (physical structure level).

- Generation of a knowledge database using the embodiment-level abstraction technique.

- Establishment of a method for generating multifunctional designs inspired by various multiscale geometries found in biological systems.

- Establishment of quantitative parameters for selecting between different biological features that exhibit the same function.

- Creation of novel multifunctional bio-inspired design concepts utilizing the abstraction, method, and quantitative parameters.

This thesis is organized as follows:

- Chapter 2: discusses the existing frameworks, and tools, for BID, and the current state-of-the-art methods for the multifunctional BID. Moreover, the chapter provides a comparative analysis of the methods for multifunctional BID.

- Chapter 3: presents the new approach in abstracting the embodiment function exhibited by the biological features as a combination of the integrated structure and the structural strategy. Detailed discussion is given on the knowledge database extracted in this research comprising about 50 biological features and their embodiment functions as a combination of integrated structures and the structural strategy,

- Chapter 4: presents the process of classification and mapping of the biological features to their respective geometric designations named Domains. The Domains are namely, Surfaces, Cellular Structures, Cross-sections, and Shapes. The biological features are further mapped to their respective tissues from which they originate. Furthermore, this chapter presents the idea of the expansion of the classification system to accommodate the classification of a vast variety of biological structures that do not comply with the current definitions of the current Domains.

- Chapter 5: presents the quantitative criteria (parameters) for the selection of relevant biological features, from those that exhibit a similar functionality and possess the same geometrical relevance.

- Chapter 6: presents the details of the complete process model of a bio-inspired concept generation system termed the Expandable Domain Integrated Design (xDID) Model.

- Chapter 7: presents the application of the idea-generation system through case studies by generating novel multifunctional early-stage embodiment designs. Three case studies are discussed namely, multifunctional bio-inspired painless sutures, multifunctional bio-inspired non-pneumatic tire design, and effective heat transfer and low-pressure drop structures for aerospace applications.

- Chapter 8: presents the conclusions and scope for future work.

2

Frameworks, Methods and Tools for BID - A Literature Review

To utilize nature's principles and strategies many frameworks, methods, and tools were developed. Within the reported literature, there exist numerous definitions of frameworks and methods. These definitions are subjective and contingent on the specific evaluations conducted within the Bio-Inspired Design (BID) process. The study by Fu et al., [34] described methods such as Design Analogy to Nature Engine (DANE) [26], IDEAS-INSPIRE [11], multi-biological effects (MBE) [35] and UNO-BID [36] as knowledge representation methods that use textual representation to describe the entire system. *AskNature* [37] and IDEAS-INSPIRE are represented as knowledge data structures. The **S**tructure-**F**unction-**B**ehaviour **(SBF)** used in DANE and SAPPhiRE (**p**arts, **s**tate, **o**rgan, **p**hysical effects, **i**nput, **p**hysical phenomenon, and **a**ction) construct used in IDEAS-INSPIRE are described as feature recognition techniques. Similarly, in various research studies, SBF and SAPPhIRE constructs have been classified as techniques for biological abstraction or representation [12, 38]. Additionally, methods like MBE and function-basis are grouped within the same biological representation category [39]. A study conducted by Goel and Hancock [40] categorizes frameworks and methods as techniques for information processing. Conversely, methods like IDEAS-INSPIRE and DANE are labeled as computational tools with functionally indexed libraries. An evaluation of tools for BID [36] categorizes frameworks as biomimetic process models, and analogical representation constructs, including SBF, SAPPHIRE, Four-box, and BioM, as abstraction tools. Furthermore, approaches such as taxonomy and TRIZ are categorized as transfer tools, while *AskNature* is identified as an application tool. [41]

In this research, drawn from the work of Wanieck et al., [42] **Frameworks** are defined as guides detailing the process of emulating a biological principle or strategy through a series of steps. **Methods**, on the other hand, outline the specific procedures for carrying out the steps outlined in a framework, and **Tools** assist in executing those steps. The following sub-sections will introduce the existing frameworks, methods, and tools. The content of this chapter has been reported in Designs journal as a Featured Article [41]

2.1 Reported Frameworks for BID

A typical series of steps in the bio-inspired design process typically begins with problem definition, followed by problem abstraction. Next comes the search for a potential biological analogy, followed by the translation of that analogy into a solution. These steps are shared by approaches such as the Alborg bio-inspired design, Biomimicry Design Spiral, and bio-solution design [43]. Lenau et al.'s systematic research survey [33] found that frameworks including the ISO model [33], Biomimicry Design Spiral [44], Georgia Tech model [27], Paris Tech model [8], and DTU Bio-cards [45] also adhere to similar steps, albeit with notable distinctions between each framework. [41]

Frameworks such as the Biomimicry design spiral have a value addition of using a taxonomy to arrange the biological systems which would assist in the relevant retrieval and selection of the relevant biological analogy [44–46]. A unified bio-inspired design framework (UNO-BID) by Fayemi et. al [36] comprises an eight-step approach from problem definition to application. This eight-step unified framework presents a detailed sequence of steps to perform a biomimetic process. Figure 2.1 shows the steps and sequence provided by different frameworks that represent the entire flow of a biomimetic process. Most of the frameworks follow a common approach starting from the problem definition/ formulation, followed by abstraction/analysis, translation of biological principles to engineering principles, and emulation and validation of the translated principles.

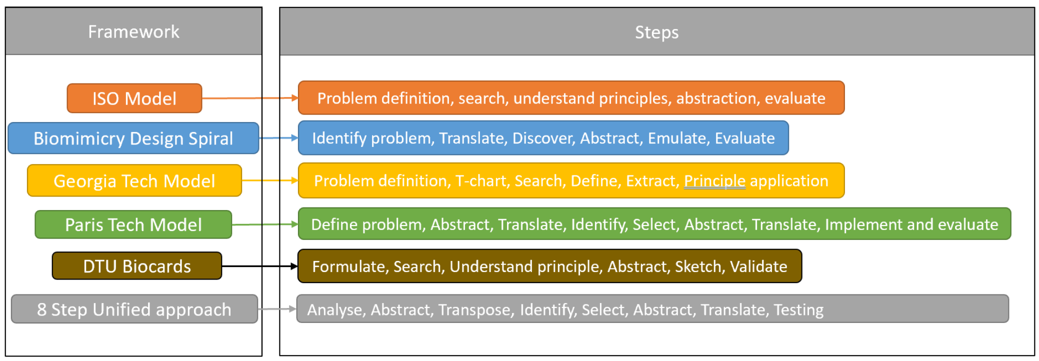

Figure 2.1: A schematic of the existing bio-inspired design frameworks.

2.2 Reported Abstraction (representation) techniques for BID

IDEAS-INSPIRE [11] is a computational design system implemented on the SAPPhIRE model construct. The SAPPhiRE model emphasizes the representation of biological analogies at a systemic level, elucidating the interactions among constructs, which encompass parts, states, organs, physical effects, input, physical phenomena, and actions. The IDEAS-INSPIRE approach strives to generate innovative biomimetic solutions by establishing causal relationships between biological systems and engineering systems. Designers analyze both natural and analogous artificial systems to devise novel solutions for engineering challenges.

DANE [26] is a knowledge-based CAD system that integrates the Structure-Behavior-Function (SBF) model for representing biological systems. This computer-aided system encompasses an ontology of structure, behavior, and functions. The DANE method assists designers in identifying a pertinent biological analogy, comprehending its functionality, and then extracting, abstracting, and applying the biological model to address an engineering problem.

IDEAS-INSPIRE and DANE employ a functional modeling technique to abstract the functions of a biological system. This technique operates at

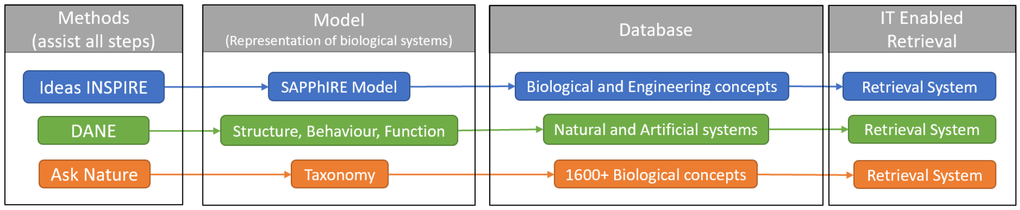

Figure 2.2: Existing methods along with their abstraction technique used for describing the biological features and their corresponding database for BID.

the system level and elucidates the interactions among different components within a system. Functional modeling involves the use of a function structure diagram to extract the biological phenomenon or strategy, thus assisting a designer in generating a biomimetic design concept [47]. According to Nagel [48], functional modeling is the process of abstracting functional information from artifacts through design activities, which can include flow-based, SBF, and other functional modeling techniques. Further detailed information on functional modeling can be found in chapter 3. Figure 2.2 presents the representation technique employed by various methods and the development of a database of biological and artificial systems that are described using those abstraction techniques.

Moreover, Nagel et al [49] delved further into utilizing functional modeling techniques to generate Biomimetic design concepts. This process involves analyzing a biological solution and pinpointing an engineering solution that shares a similar essence, ultimately creating an engineering concept that mirrors a biological system Additionally, Nagel et al [50] introduced analogy categories to represent and contextualize a biological system. These categories fall into two types. The first type covers the physical aspects of the biological system, encompassing form, surface, architecture, and material. The second type includes the non-physical attributes of the biological analogy, like function, material, and process. However, it's essential to note that these analogy categories primarily aim to explore the biological analogy and don't delve deeply into analyzing the biological systems. For instance, the "Form" category addresses visual aspects such as shape, geometry, and aesthetics but doesn't offer a detailed analysis, like specifying "What exact form?" or "Which biological feature or underlying tissue contributes to achieving a particular function? [41]

2.3 Reported Tools for BID

ASK NATURE [37] is an online tool that operates as a functionally indexed database of biological systems. It is constructed on a taxonomy that effectively organizes biological information. ASK NATURE functions by retrieving biological analogies based on user queries.

The Four-Box model [51] has evolved from an SR.BID (Structural Bio-Inspired Design) schema that follows the SBF approach. This tool assists in the problem formulation stage of the BID process. It identifies four crucial conceptual categories, each representing a box where biological analogies can be classified. These four categories include:

- **Function**: which pertains to the actions a system must carry out.
- **Operational environment**: which relates to the location and conditions in which a system operates.
- **Specifications**: encompassing factors like material, shape, physical characteristics, and so forth.
- **Performance criteria**: indicate the extent to which a system fulfills its intended task.

To evaluate an analogy, a T-chart is suggested, where the retrieved biological analogy is assessed using these four identified categories.

A task-model tool [52] is employed to assess the macrostructural behavior in biologically inspired design through task analysis. Much like the principle of functional decomposition, this tool breaks down a task into its constituent sub-tasks. The model incorporates compound analogy, solution-driven, and problem-driven approaches. If the initial solution only address a portion of the problem, a new sub-task is generated to resolve the remaining aspect. The ultimate solution is the amalgamation of all solutions obtained for each sub-task.

A thesaurus bridging engineering and biology [48] enables designers to search for and retrieve analogies using terms derived from a widely recognized function-based lexicon. This lexicon combines pairs of verbs and nouns, or functions and flows. A function denotes an action or transformation, while a flow refers to a material, energy, or signal. There exist eight classes of functions and three classes of flows [53]. The engineering-to-biology thesaurus finds application in problem formulation and in the search for engineering solutions that replicate biological functions, thereby generating BID solutions. Figure 2.3 shows the translation tools employed to aid the BID process by bridging the gap between biological terminology and engineering terminology. Likewise, an innovative tool for generating bio-inspired concepts [54]

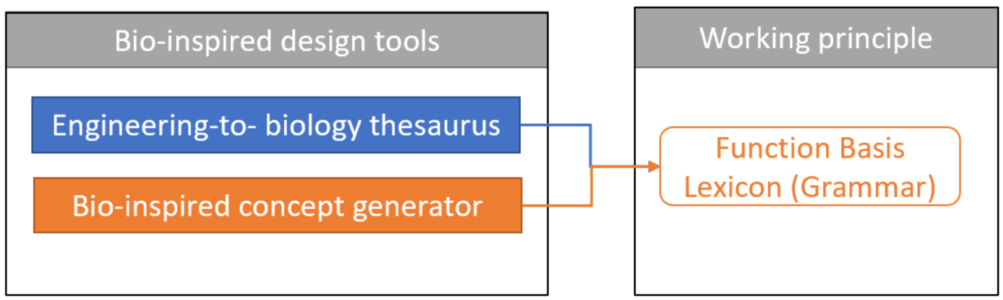

Figure 2.3: Translation tools based on function basis lexicon. These tools offer translation of biological functions into engineering functions based on the function basis lexicon.

was created by incorporating function-centric design techniques that operate within the framework of identification, translation, iteration, and conceptualization. At the heart of this tool lies the system-level analysis, which employs functional modeling as its technique. This tool leverages a lexicon based on functionality to break down a problem statement into aspects like function, structure, behavior, or strategy. To handle the query and search for pertinent analogies, a software known as MEMIC (automated morphological matrix search tool) is utilized.

SEABIRD-Scalable [55] is a tool designed to aid in the search phase of a systematic BID. It facilitates the linkage between products outlined in patents and the biological species along with their strategies that are systematically documented in the corpus. The concept of bio-transferability is introduced for categorizing, prioritizing, and arranging biological analogies, employing SMAA (Stochastic Multi-Criteria Acceptability Analysis) techniques [56]. However, it's worth noting that this approach employs descriptive metrics for offering decision support. Additionally, proficiency and comprehension of the criteria are required for these techniques, and occasionally, they may yield straightforward analyses.

Design heuristics are methodical approaches employed in the process of generating ideas. They rely on a knowledge-based approach acquired through extensive experience. Yet, applying design heuristics to address practical design challenges necessitates detailed information about materials, their properties, and usage, which can be challenging to acquire in the early stages of product development [57]

BioM is a database developed by Jacobs et. al. [58], which delves into over 380 cases culled from the literature and categorized as 'biomimetics'. This resource facilitates the retrieval of biological analogies. Nevertheless, the study underscores the importance of deconstructing biological principles to grasp which specific biological forms, processes, or interactions underlie a given function.

2.3.1 IT enabled tools

In addition to the reported tools, other tools use machine learning and Artificial Intelligence (AI) techniques to extract and organize biological analogies. As shown in Figure Figure 2.4, tools like BioTRIZ [59], SEABIRD [55], FOBIE, PAnDA, D-Apps, and Dracula implement data processing algorithms like retrieval, mapping/clustering, natural language processing, rule-based text mining, and function basis respectively. Mostly these IT tools acquire the data from literature sources such as patents, and academic/research papers. Current IT-enabled tools have the potential to extract keywords, feature descriptions, etc. Additionally, semantic knowledge graphs are employed for idea generation. These knowledge graphs offer a visual representation of two entities, concepts, or objects along with their shared attributes. Figure 2.5 illustrates an example of a semantic network graph representation (TechNet) utilized for idea generation, incorporating data sources from US patent data spanning from 1976 to October 2017. [10,60] Furthermore, Large Language Models (LLMs) are employed to extract valuable data by generating ontological knowledge graphs. These visually represented graph structures facilitate the discovery of new insights for research and aid in understanding missing information [61].

2.4 Reported Multifunctional BID methods

It is imperative to understand how biological systems become a source for the generation of multifunctional designs. While there are numerous approaches available for BID, the majority of them focus on emulating a single func-

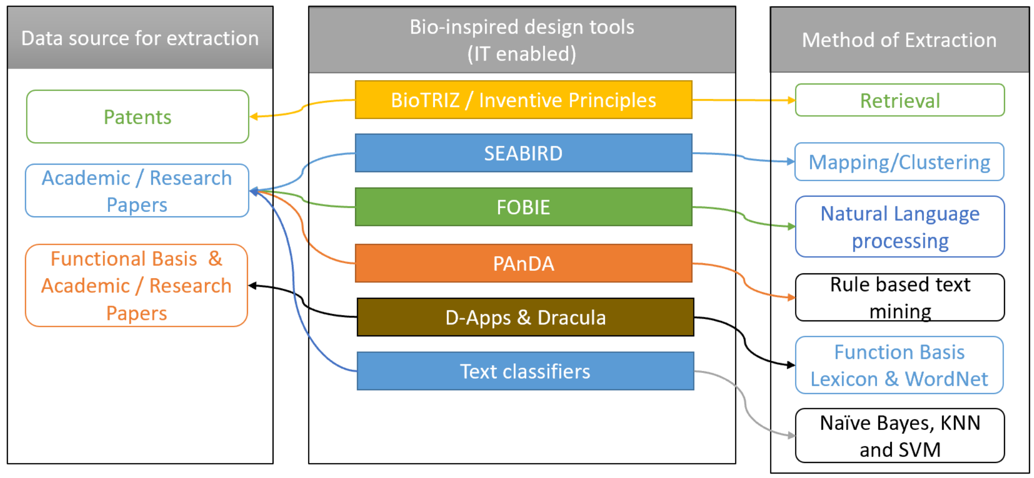

Figure 2.4: IT-enabled tools that extract, classify, cluster, and map biological systems from the available data sources such as academic articles, patents etc.

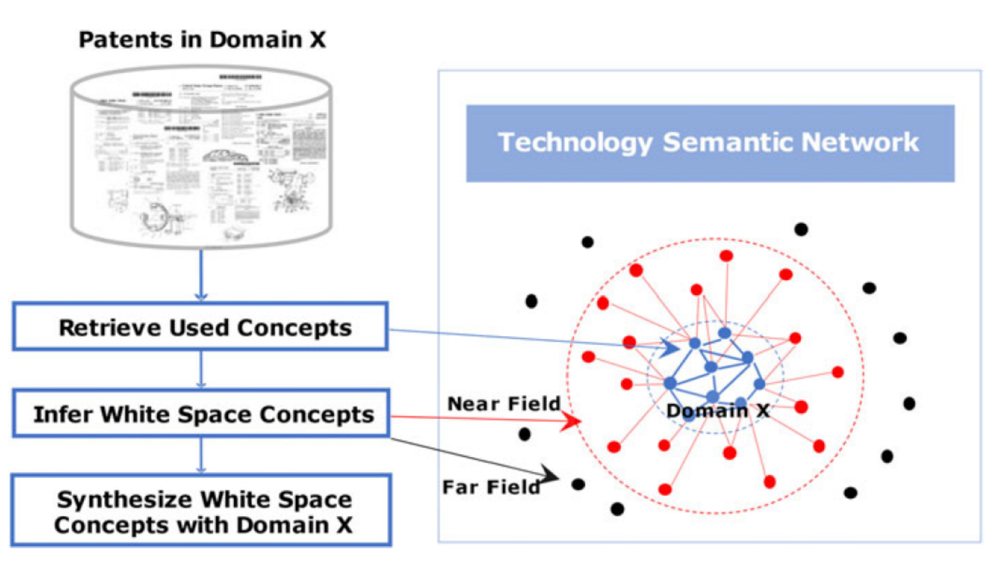

Figure 2.5: Representation of TechNet Semantic graph generation [10]

tion. Only a limited number of methods documented in the literature aid in the creation of multi-functional BID. The following are the approaches that contribute partially to generating multi-functional bio-inspired designs.

BioTRIZ [59] is a BID approach rooted in TRIZ techniques. It is represented by a 6 × 6 matrix that encompasses parameters to be enhanced, including some parameters that lead to a contradiction. These parameters encompass substance, structure, time, space, energy, field, and information adaptation [33]. While BioTRIZ may not explicitly outline a method for developing multifunctional structures, it does facilitate the problem definition phase in supporting multifunctionality within BID [58]. This method offers a means to conduct a multifunctional problem definition and search for pertinent biological analogies.

Bhasin et al. [12] introduced a tool based on product architecture that employs a function-sharing approach for multifunctional BID. This method focuses on abstracting biological analogies or adaptations through function-sharing and utilizes hybrid product architecture tools like the reduced function-means tree to represent interactions within these analogies or adaptations. The reduced function-means tree employs three constructs—structure, behavior, and function—along with four interactions—(a) is solved by, (b) requires function, (c) physically realized by, and (d) interacts with—to represent a biological analogy.

The function-sharing approach involves a single biological feature serving multiple functions. For instance, shark skin simultaneously performs anti-biofouling and drag-reducing functions. The essence of this product-architecture-based method lies in abstracting biological analogies or adaptations through the reduced function-means tree, and then amalgamating the chosen analogies to acquire the necessary features for designing a product. The selection of these analogies is contingent on a specific criterion that hinges on the utilization of behaviors and structures of pre-existing functions. However, this method tends to resolve functions that can be amalgamated or simplified into a single overarching function. Consider the micro projections found on a lotus leaf, which serve dual functions: repelling water (superhydrophobic) and repelling oil (superoleophobic). These functions essentially centered on liquid repellence, can be effectively represented as a unified function—repelling liquids.

Badarnah and Kadri [62] propose BioGEN, a method that facilitates the representation, identification, abstraction, and systematic selection of biological principles. The process commences with extracting biological analogies that carry out the desired function, which are termed "pinnacles." Subsequently, an in-depth analysis is conducted on the strategies and principles employed by these biological analogies. This analysis may lead to the challenge of convergent evolution, wherein more than one biological analogy can address similar problems. To mitigate this complexity, the "pinnacles" are categorized, allowing for the extraction of the most prevalent feature among them. These categories encompass (a) process, (b) flow, (c) adaptations, (d) scale, (e) environmental context, (f) morphological features, (g) structural features, (h) material features, and (i) other features. The most dominant feature identified is referred to as the "imaginary pinnacle." It is possible to have multiple imaginary pinnacles, in which case the selection is made using the design-path matrix. Ultimately, the chosen strategies are integrated to formulate a design concept.

The trimming design method, derived from TRIZ techniques, involves utilizing existing resources by removing detrimental components to enhance a product. Additionally, this method integrates the replacement of specific system components inspired by biological strategies or adaptations. This process encompasses three steps:

- Performing functional analysis of the system to identify inefficient or harmful components through cause-effect-chain analysis (CECA).
- Searching and identifying trimmed functions within the biological (MBE) database [35] and selecting the optimal solution using the fuzzy comprehensive evaluation method.
- Implementing the biological solution into the system to enhance performance.

The fuzzy comprehensive evaluation method assesses three factors: compatibility, completeness, and flexibility [36].

The Multi-bionics approach aims to enhance the functionality of bionics by utilizing a biological coupling mechanism [35, 63]. Similarly, the Multi-biological Effects (MBE) method integrates the concepts of biological coupling and TRIZ techniques to achieve multiple functions. This method incorporates a diagrammatic model that depicts biological elements, as well as a data structure that serves as a rich source of biological inspiration and allows for integration with other innovative design methods [35].

Biological coupling operates on the premise that biological functionality arises from the combination and interactions of various factors, including morphologies, structures, materials, and constitutions of an organism. For instance, the lotus leaf's ability to repel water and self-clean results from the combined effects of its non-smooth morphology, micro-nano composite structure, and waxy materials [63]

The function-means tree model [64] is employed to visually represent multifunctional organs or means. This aids designers in determining which functions to merge and then initiating a search for a relevant biological analogy that accomplishes those merged functions. The method involves classifying functions into categories like energy delivery functions, regulating functions, support functions, and auxiliary functions. These classified functions are then combined based on specific requirements. Subsequently, a search is conducted for a pertinent biological analogy capable of addressing these combined functions. This method draws inspiration from instances where a single organism addresses multiple challenges. In this context, the term "function" denotes the desired output, while "means" refers to the organ or component through which the function is realized.

The compound analogical design method [65] operates on the principle of breaking down a problem statement into smaller sub-problems. It then involves searching for pertinent biological analogies or strategies that address each of these sub-problems. The ultimate solution is derived by combining the solutions obtained for all sub-problems.

The system-of-systems BID method [66] involves categorizing various biological species based on their functionalities. From each of these groups, a champion species is selected and then these champions are integrated to create a multifunctional and reconfigurable robot. To elaborate, species demonstrating a specific desired biological functionality are grouped together in list 1, while those exhibiting a different desired functionality are categorized in list 2, and so forth. A champion species is chosen from each list using Pugh analysis. Finally, the distinctive features of these champion species are combined to guide the design and development of multifunctional robots.

A systematic literature review conducted by N. Svendsen and T. A. Lenau [67] identified several multi-functional design methods, including compound analogical design [65], BioTRIZ [59], and the work of Wolff in 2017 [68], as currently available methods that aid in achieving multi-functionality. It's worth noting that Wolff's work [68] and compound analogical design [65] both stem from the same principle of problem decomposition. Additionally, the systematic review by N. Svendsen and T. A. Lenau [67] suggests that the future direction of BID should involve transitioning from a problem-driven approach to a solution-driven approach. This shift would facilitate the development of multifunctional systems.

Nagel [69] presented a comprehensive methodology for supporting the systematic generation of bio-inspired conceptual designs in BID. The process, illustrated in Figure 2.6, encompasses four major and overlapping steps in BID concept generation. The initial step involves identifying biological systems that exhibit various functions, employing an organized search tool based on Natural Language Processing (NLP) and functional keyword search—a method commonly referred to as inspiration facilitators for BID. The second step focuses on representing biological systems, where functions are abstracted into a biological functional model using functional modeling techniques. This technique entails describing the function of the entire product/system through schematic diagrams, behavioral diagrams, and integrated functional blocks illustrating each component and its connections. The subsequent step involves translating biological functions into verb-noun pairs through the functional basis lexicon. This lexicon represents the transformation (verb) of flows (noun), encompassing material, signal, or energy necessary for an engineering system. A crucial aspect of the functional basis lexicon is its ability to translate context from the biological to the engineering domain, identifying characteristics that can be replicated through engineering means. Following translation, the next step involves conceptualizing bio-inspired engineering systems, with the concept generation step employing two approaches

- The first approach entails constructing a biological functional model of a biological system and using this model as a query to extract potential engineered solutions from a design repository. For each function/flow pair, a set of engineered components is retrieved. Subsequently, the designer selects the pertinent components to formulate a comprehensive conceptual design that emulates the biological system.

- The second approach involves translating customer needs into engineering specifications and functional requirements. A black box conceptual functional model is generated and queried in a biological repository. A collection of biological systems with similar functions is then retrieved to guide the development of an engineered product that aligns with these identified functions.

Figure 2.7 presents the overview of the abstraction approaches, multifunc-

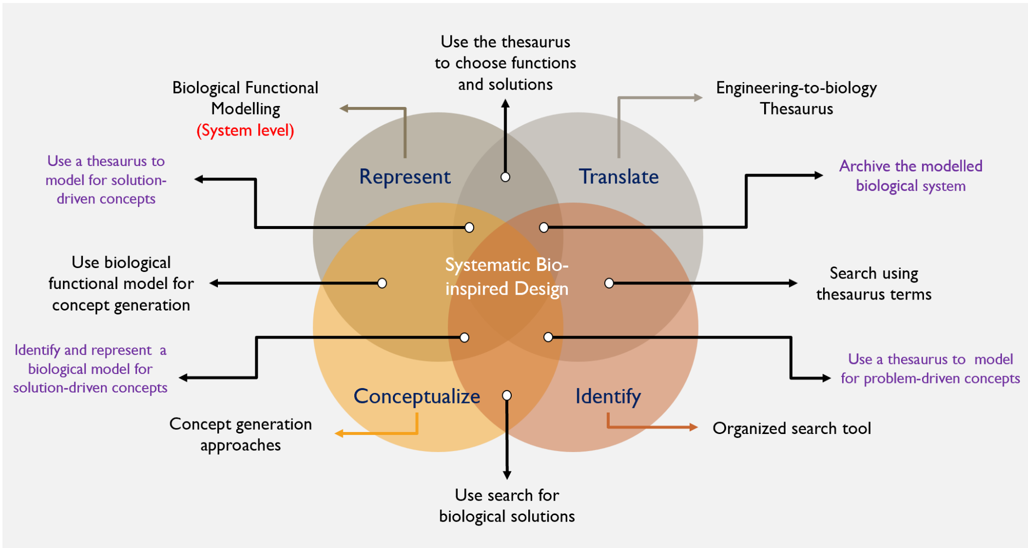

Figure 2.6: Systematic BID which comprises the four important steps namely, Identification, Representation, Translation, and Conceptualization

tional design methods, and the tools used for assisting the design methods. The existing abstraction techniques utilized to represent the biological organism, follow a system-level and a product architecture-based approaches. The design methods developed for multifunctional concept generations are either inspired by a single organism solving multiple functions or from a combination of features from multiple organisms. A detailed explanation of the abstraction techniques is presented in Chapter 3, followed by details of the new method developed to achieve multifunctional and early-stage embodiment designs.

2.5 Comparative Analysis of Multifunctional BID methods

It is necessary to analyze the methods for multifunctional BID for enhancement and for the generation of a more accurate and rapid ideation process.

The analysis of methods for multifunctional designs was conducted based on nine specific criteria:

- Source of inspiration: Single organism or multiple organisms.

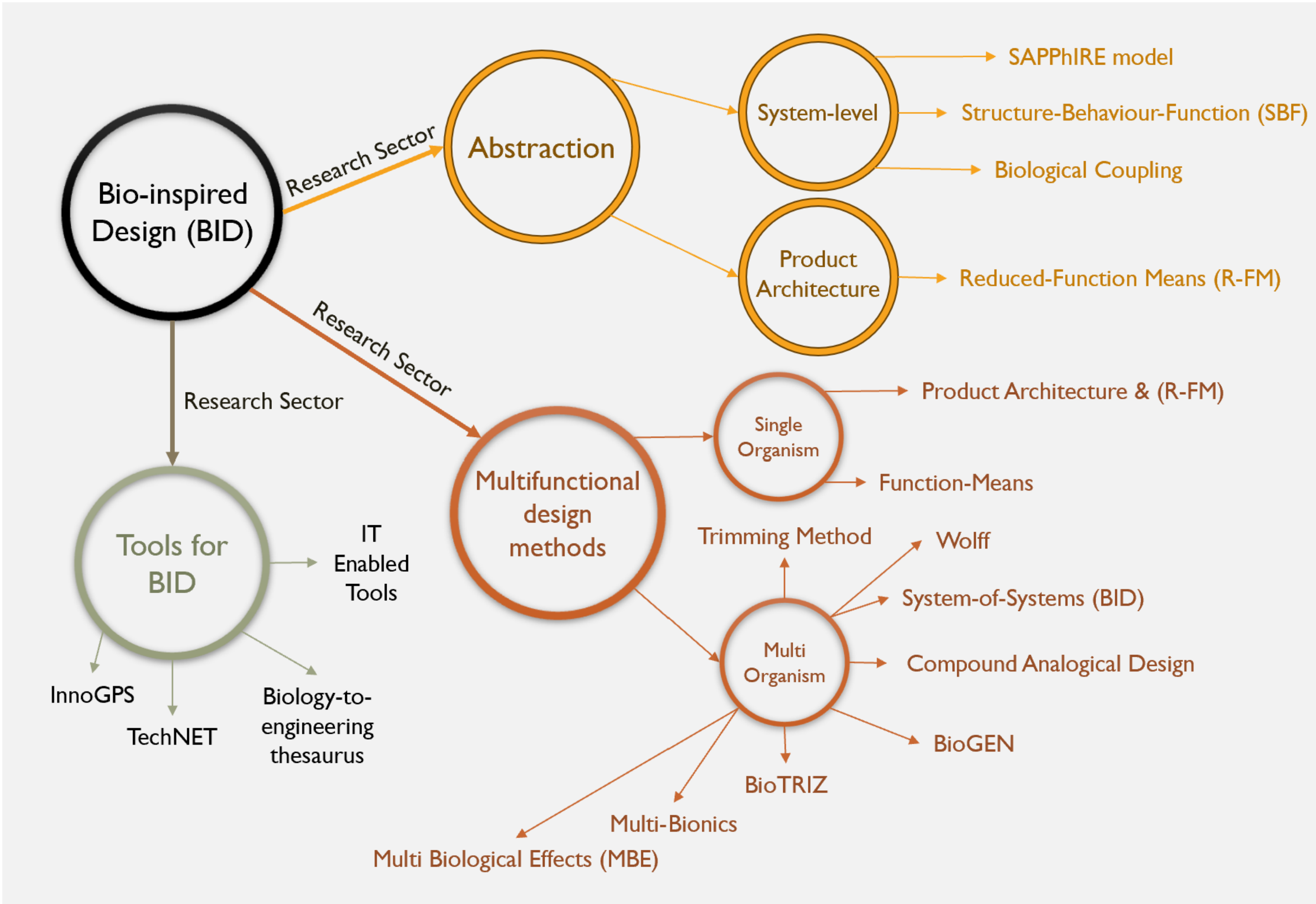

Figure 2.7: Overview of the Bio-inspired Design's research sectors and the existing abstraction techniques, methods, and tools that assist in concept generation.

- Approach: Problem-driven or solution-driven.
- Principles: Functional decompositions, inventive principles (TRIZ)/trade-off, biological coupling, and functional sharing.
- Classification of features observed in a biological system.
- Criteria for selecting biological analogy.
- Feature parameters/factors for integrating analogies.
- Assistance in selection under convergent evolution.
- Simulation/testing of generated designs.
- Availability of a dedicated database and IT-enabled tools.

Figure 2.8 presents information that outlines a comparative analysis conducted on methods for multifunctional BID. This analysis indicates that the majority of these methods draw inspiration from multiple biological organisms, resulting in the attainment of diverse functions through a combination of these systems. Conversely, it is evident from the analysis that only the reduced function-means (function sharing) and function-means methods draw their inspiration from a single organism, illustrating the capacity of a single biological system to address multiple functions. In terms of approach criteria, most methods adopt a problem-driven approach, with only the reduced function-means method adopting a solution-driven approach. Regarding principles, the majority of methods employ function/problem decomposition, breaking down a problem into various sub-problems and devising solutions for each. The reduced function-means and function-means methods are unique in their adherence to function-sharing, while the BioTRIZ method adheres to TRIZ techniques. Finally, MBE and multi-bionics methods adhere to biological coupling principles. [41]

The analysis revealed several distinctions among the methods for multifunctional designs:

1. Only the function-means method categorizes features into energy delivery, regulation, support, and auxiliary functions. Other methods lack this classification.
2. Regarding the selection of biological analogy, different methods employ distinct approaches:

- Reduced function-means relies on behaviors and structures of existing functions.
- System-of-systems BID uses Pugh analysis.
- BioGEN utilizes the design path matrix.
- The trimming method employs a fuzzy comprehensive evaluation.

3. None of the methods provide specific parameters or factors for integrating different biological features to achieve multifunctionality.

4. In the context of assisting selection under convergent evolution (choosing from multiple biological organisms addressing the same function), only system-of-systems BID and BioGEN offer aid in the selection process.

5. Most methods conclude at the conceptual stage without validation through simulation or testing. The system-of-systems BID method, however, is specifically aimed at one particular application that is developing re-configurable robots.

6. In terms of database and IT-enabled tools, only BioTRIZ, MBE, and the trimming methods have their own respective web-based tools and databases.

7. None of the methods have addressed the integration of multiscale features responsible for achieving specific functions.

Following a thorough analysis of the current state-of-the-art methods for multifunctional bio-inspired designs, the following gaps have been identified.

1. There is a need for a more streamlined abstraction of biological features mapping their functions and structure and the structural configuration to enhance the rapidity of idea generation.

2. Secondly, there is a need for a new approach to the classification of biological features based on their geometric designations. Thus aiding the designers in the selection of features based on function, feature, and geometry. This enables the combination of features exhibiting different functions to generate multifunctional designs.

3. There is a need for an expandable knowledge database comprising the function, structure, and geometry to enable IT-based tools to visualize and retrieve information.

4. There is a need for quantitative criteria (parameters) for the selection of relevant biological analogies from those features that exhibit the same functionality and have a similar geometric relevance.

As depicted in Figure 2.9, the first part of the thesis introduces a novel embodiment-level abstraction technique. The second part presents the novel DID method for generating multifunctional designs, including meta-level design parameters for selecting between the features that solve the same function. Additionally, xDID expands on the DID method to facilitate the classification of complex biological features. Finally, the system's robustness in generating multifunctional design concepts is tested through the creation of multifunctional bio-inspired design concepts.

In the subsequent chapters, Chapter 3 introduces a new abstraction technique of biological features, followed by the classification method presented in Chapter 4, and the parameters for selection in Chapter 5.

Method	Inspiration	Approach	Principles	Classification of features in biological systems	Criteria for selecting biological analogy	Parameters for integration of analogies	Assistance in convergent evolution	Simulation and testing of generated designs	Database and IT enabled tools
Reduced function means (RF-M)	Single organism	Lead to solution-driven	Function sharing	⚫	Behaviours and structures that uses already existing functions	⚫	⚫	🔵	🟠
Compound analogy	Multiple organisms	Problem-driven	Function decomposition	⚫	🟠	⚫	⚫	🔵	⚫
BioTRIZ	Multiple organisms	Problem-driven	TRIZ Techniques	⚫	🟠	⚫	⚫	🔵	Web tool
System-of-systems BID	Multiple organisms	Problem-driven	Function decomposition	⚫	Pugh Analysis	⚫	yes	Prototype (Robotics application)	⚫
Multi-Bionics	Multiple organisms	Problem-driven	Biological coupling	⚫	🟠	⚫	🟠	🟠	🟠
Multi-Biological Effects (MBE)	Multiple organisms	Problem-driven	Biological Coupling	⚫	🟠	⚫	🟠	🟠	Multi Biological Effects (DB)
Function Means	Single organism	Problem-driven	Function decomposition & Function sharing	Energy delivery and regulation	🟠	⚫	⚫	🟠	⚫
BioGEN	Multiple organisms	Problem-driven	Function decomposition	⚫	Design path matrix	⚫	yes	🔵	⚫
Trimming method	Multiple organisms	Problem-driven	Function decomposition	⚫	Fuzzy comprehensive evaluation	⚫	⚫	🔵	Multi Biological Effects (DB)
Wolff	Multiple organisms	Problem-driven	Function decomposition	⚫	🟠	⚫	🟠	🟠	🟠

⚫ Do not assist 🔵 Only concept design 🟠 Inadequate / No information

Figure 2.8: Comparative analysis of the state-of-the-art multifunctional BID methods under nine specific criteria

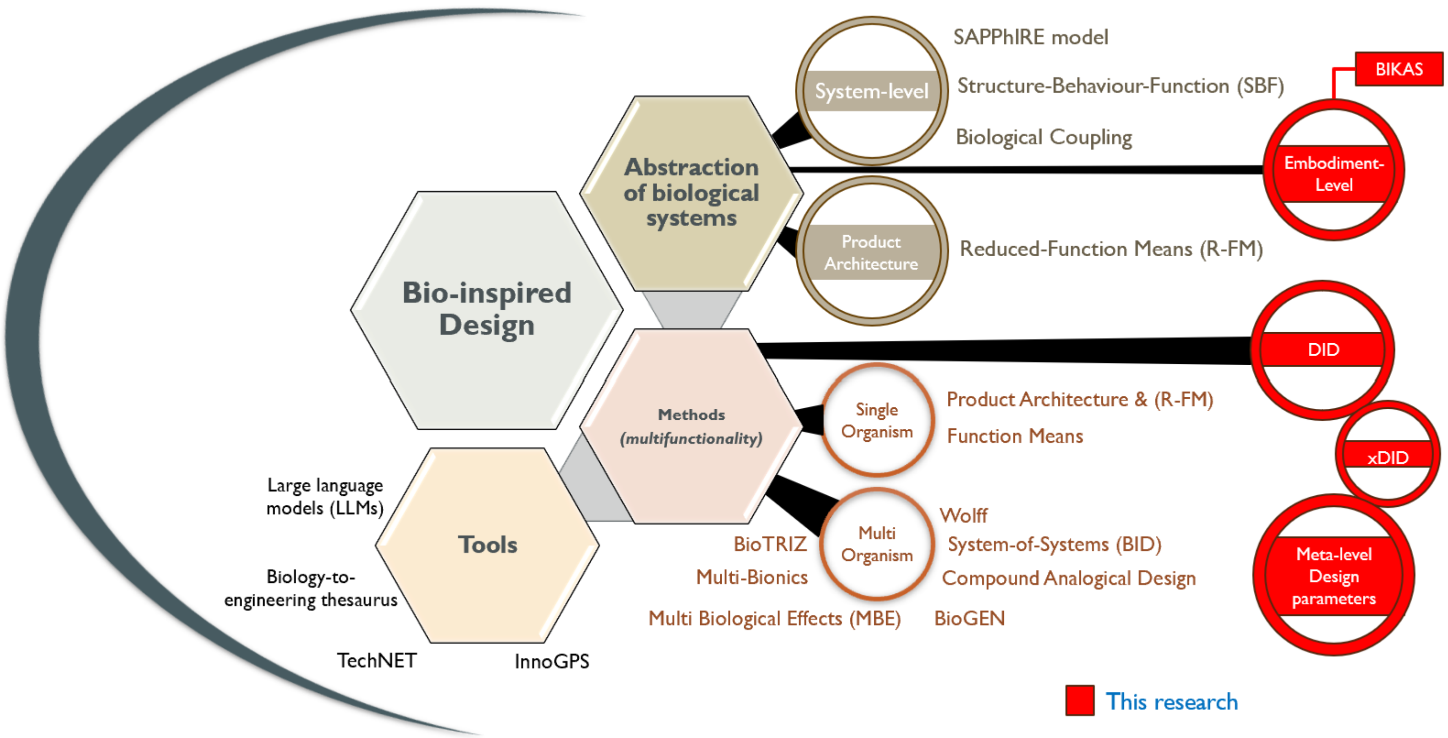

Figure 2.9: Depicting the components of the proposed ideation system and how they align with different research areas within the field of Bio-Inspired Design (BID)

2.6 Summary

Bioinspiration and bio-inspired design constitute a continuously expanding field, marked by the development of various frameworks, methods, and tools that harness nature's principles and adaptations. However, many existing methods predominantly emulate singular functions or strategies, with only a select few aimed at achieving multifunctionality. Approaches such as Bio-GEN, A system-of-systems BID, BioTRIZ, Trimming Method, Compound analogy, multi-bionics, and MBE utilize combinations of functions from multiple biological organisms to achieve multifunctionality. Notably, only the Function-Means and Reduced Function-Means-based product architecture methods involve a single organism addressing multiple functions. Within the context of the classification of biological features, only Function-Means stands out for classifying diverse functions such as energy delivery, regulation, support, and auxiliary functions.

Moreover, comprehending the biological functions exhibited by organisms necessitates the abstraction of biological systems. The existing abstraction techniques analyze biological organisms at a systemic level, underscoring the requirement for an abstraction technique at the embodiment level to streamline complex system-level abstractions. Furthermore, a classification method that facilitates the swift selection and amalgamation of biological features for the development of multifunctional conceptual designs is essential.

Part II

Abstraction of Biological features

3

BIKAS: Knowledge database to support the mapping of biological feature to its function, structure, and structural strategy

The current leading approaches in BID research involving the abstraction of biological analogies employ functional modeling or function representation methods to grasp the overall functions of the biological system. However, these techniques represent the functions of biological organisms at a system level. Representation of highly complex features at the system level often leads to missing out on intricate details of highly complex structures. Although methods such as Biological coupling [63] reported that functions exhibited by biological features are due to a combination of various biological features intricately connected. However, the representation of biological features at their granular level at their embodiment level becomes imperative to understand the biological feature's multiscale structure and their configuration that plays a key role in exhibiting various functions. Figure 3.1 depicts the overview of the system-level abstraction techniques and the technique introduced for the representation of the function exhibiting biological features at the embodiment level. Moreover, in convergent evolution, distant

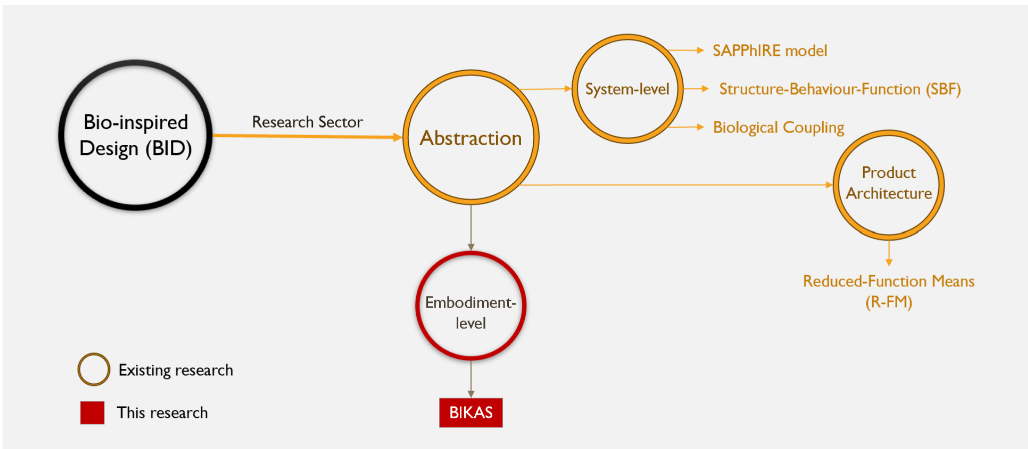

Figure 3.1: Overview of the existing system-level abstraction techniques and the embodiment-level abstraction technique detailed in this chapter.

biological features exhibit similar functions in different ways. To provide designers with specific details of the biological multiscale structure, and their configuration, necessitates the abstraction of the biological features at their physical structure and the generation of a knowledge database to address the differences in biological features that exhibit the same functions (Convergent evolution approach). However, the embodiment-level function description is easily integrated into any existing system-level representation techniques for a complete analysis of the biological systems. This chapter details the functional modeling technique followed by the embodiment-level function abstraction of fifty biological organisms. The content of this chapter has been reported in Data Intelligence journal [70]

3.1 Functional Modeling Technique

Abstraction frameworks like SAPPhIRE [71] and DANE (SBF) [72] utilize similar techniques to those employed in functional modeling to represent biological systems. The functional modeling technique dissects a complex physical product or system, considering connections between different components, substances within the components, prerequisites, outcomes, and state changes and transitions. [72]. Function modeling entails expressing, representing, or describing a product or system using a high-level abstract language that depends on its functionality [73]. These systems can be delineated using process flow block diagrams or hierarchical tree models to depict functional behavior [74].

3.1.1 Examples of reported abstraction techniques for biological systems using Functional Modeling

This section showcases examples of system-level abstraction techniques employed in analyzing biological systems. Each of these techniques focuses on evaluating the entirety of biological systems, considering all components comprising the system and their interactions.

SAPPhIRE Model

The SAPPhiRE model of causality used in the IDEAS-Inspire framework works on abstracting the biological system in terms of *Parts*: represents a set of physical components, *State*: represents the attributes that define the properties of the system, *Organ*: represents the structure necessary for a physical effect to manifest, *Physical phenomenon*: represents the potential changes associated with a given physical effect, *Action*: describes the high-level interpretation of the changed state (or) creation of inputs.Figure 3.2 presents the flowchart of the abstraction technique of the SAPPhIRE technique.The abstraction technique can be further elaborated with an example of the function of a ***venus flytrap***: A carnivorous plant that feeds on insects by trapping them in their leaves. The following describes each component of the Venus flytrap using the SAPPhIRE model.

- Action: feed on insects by trapping the insects inside the leaves
- Input: A chemical stimulation by using electrical signals to the glands to produce a scent to attract insects.
- Physical phenomenon: Emitting the generated scent inside the leaf/trap. Thus, attracting insects towards the trap.
- Organ: The sent gland that produces the chemicals that emit the scent. Describing the composition of the scent.

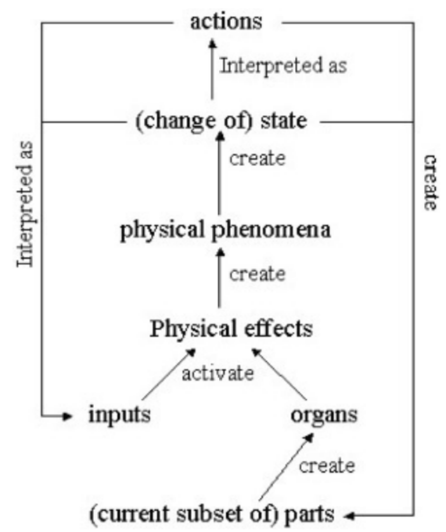

Figure 3.2: SAPPhIRE model [11]

- Physical effect: Chemical effect of the scent which affects the insect nostrils.
- State: Leaf cells' are compressed, creating tension in the plant tissue and holding the trap open.
- Parts: The nectar glands present in the leaf. These glands are made up of chemicals to stimulate the insects particularly.

SBF Model

The SBF (Structure, Behaviour, and Function) stands as an alternative modeling technique employed to abstract intricate biological systems. This modeling approach uses functions as key markers to structure the knowledge of behavior (such as state transitions) and structures. Additionally, each state transition is annotated with causal explanations. The biological system is described as a hierarchy from function to behavior. The SBF approach is elaborated below with an example of "Kidney filters Blood" adopted from [26]. The $[FN]$-X: represents the transition that occurs because of some subfunction X. $[STR - CON]$-X Y: represents the transition that occurs between the structural components X and another structural component Y.

The entire process of purification as described by the SBF approach is as follows:

- $[FN]$: Decrease surface area to volume ratio; $[STR - CON]$: Blood flow through Cortical Radiate veins to Interloper veins

- $[FN]$: Decrease in surface area to volume ratio; $[STR - CON]$: Interloper Veins to Arcuate Veins.

- $[FN]$: Decrease surface area to volume ratio; $[STR - CON]$: Arcuate Veins to Renal Veins.

Reduced Function Means (RF-M) Model

The Reduced Function Means (RF-M) is an abstraction technique that uses three constructs namely, **Function**, **Behavior**, and **Structure**, and four interactions such as *"is solved by"*, *"Requires function"*, *"is physically realized by"*, *"interacts with"* in describing the functions performed by the biological systems. For example, as shown in Figure 3.3, consider the function to increase the speed of a shark underwater, *"is solved by"* two behaviors: decrease drag and prevent bio-fouling. Furthermore, the decrease drag behavior *"requires function"* to decrease pressure drag. The pressure drag function *"is solved by"* the behavior converting the pressure drag to surface drag. The behavior of converting the pressure drag to surface drag *"is physically realized"* by the structural morphology of the shark skin. The current state-of-the-art abstraction models utilized in analyzing biological organisms operate on a systemic level. They encompass the entirety of a system's components and their interactions, including the flow of material, energy, and signals among these components [69]. System-level techniques are crucial for comprehending the various functions performed by biological systems.

However, there exists a pressing need for an abstraction technique that delineates the functions of individual components. Given the high complexity of biological systems, abstraction becomes imperative at the most granular level – the embodiment level, wherein function correlates with the physical structure. Moreover, there's a necessity to depict the multi-scale structure and its configuration, elucidating how these structures are arranged, oriented, and altered by external stimuli. The configuration of multi-scale structures plays a pivotal role in achieving specific functions.

The subsequent sections delve into the details of a novel abstraction technique that describes function at the embodiment level, amalgamating the

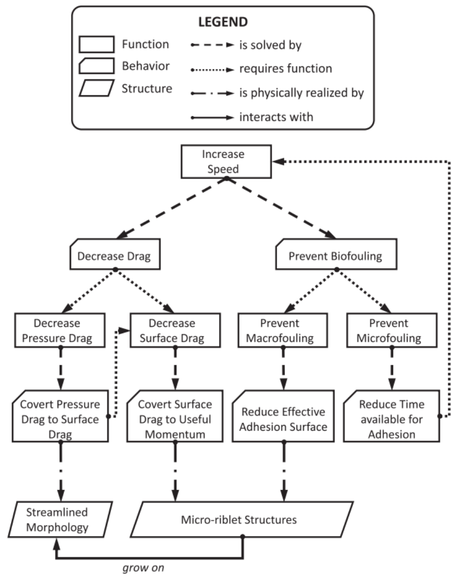

Figure 3.3: Reduced Function-Means approach for abstracting the increase speed function of a shark [12]

integrated structure with its configuration

3.2 Functions in biological systems

Lienhard et al. [75] pointed out that a natural system can be described by considering the combination of form, material, and function. Ren and Liang [63] further explained that biological functionality arises from the interplay and integration of various factors or elements such as morphologies, structures, materials, and the makeup of an organism. For instance, the lotus effect, or self-cleaning mechanism, results from the amalgamation of non-smooth morphology, micro/nanocomposite structures, and waxy materials. From a broader perspective, these contributing elements or factors are categorized into physical elements like material, structure, and shape, and non-physical elements such as biological behaviors like flexibility and lubrication. Ren and Liang [76] provided an example with earthworms, which achieve resistance to adhesion through lubrication, electro-osmosis, non-smooth morphology, and flexibility, all of which are enabled by the synergistic interaction of various body parts. Similarly, digging mole crickets are able to reduce friction, resist adhesion, and withstand wear due to the shape, structure, and surface properties of their forelegs, fore-wings, and tergum. Gao [77] pointed out that the distinguishing factor between two different biological entities with similar functionality lies in the variations of their surface micro-structures. For instance, both mosquito eyes and lotus leaves exhibit the property of superhydrophobicity, but each biological entity possesses a distinct micro-structure and arrangement that accomplishes the same functionality. This underscores that a specific property or functionality is contingent on the micro-structure and its arrangement or configuration. In a study conducted by Helfman Cohen et al [78], analyzed over 140 biological systems using a robust model that generated a set of recurring structural-functional patterns applicable to biomimetic applications. These recurring patterns encompass protrusions, tubes/channels, asymmetry, layers, intersected layers, helixes, streamlined shapes, and containers. While the study introduced a proposed Su-field model for representing function achieved through the structure in terms of components like engine, transmission, control, and working unit, it did not encompass a method for classifying, mapping, or employing function abstraction techniques for the integration and development of multifunctional conceptual designs.

3.3 Meta-level Embodiment Function

Functions in artificial or engineered products and systems can be categorized into overall, embodiment, and geometric functions. The overall function provides a broad description of the intended purpose achieved through the integration of various system components. On the other hand, the embodiment level delineates the functions of individual components, while the geometric level pertains to the specific geometric attributes [79]. The basic mechanical function corresponds to the embodiment level function, which is closely tied to the physical structure. At this level, the structure encapsulates the physical traits of a product.

Based on the definition of embodiment function provided by Deng et al. [79], the proposed function operates at the level of embodiment function, specifically at the physical structure level. This is attained through the amalgamation of an integrated structure, often occurring at multiple scales, and the strategies employed in its design. This approach offers a higher-level overview of the biological feature and its corresponding structural strategy. The detailed definition of the integrated structure (often occurring at multiple scales) and the associated 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.)" [13]
- "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.)" [13]

The following sub-section provides the methodology applied for the extraction and mapping of biological features, their functions, integrated structure, and the structural srategy.

3.4 Construction Flowchart and BIKAS

BIKAS is constructed based on case-based examples of bio-inspired design found in the existing literature. The biological systems are depicted by considering the biological feature, its attributes, and the function it performs, which result from the combination of the integrated structure and the structural strategy.

BIKAS is a distinctive knowledge dataset that involves a manual process of searching, acquiring, analyzing, and curating information. Structured knowledge bases and repositories that aim to create representation models for understanding biological phenomena, human interaction, initiation, and curation are imperative [80]. To elucidate the creation of BIKAS, a construction flowchart is essential. Construction flowcharts facilitate the replication, population, and advancement of comprehension regarding the biological features of a given biological entity. Figure 3.4 illustrates the schematic of the construction flowchart. The construction flowchart of BIKAS encompasses three phases: the Acquisition phase, Analysis Phase, and Interpretation phase. The subsequent section provides a detailed explanation of each phase.

- **Acquisition phase**: This phase comprises acquiring the bio-inspired case studies and research articles that describe biological features, their functions, principles, replication, manufacturing, and application of biological structures.

- **Analysis phase**: This phase comprises the segregation of biological features, feature characteristics, structure, and structural strategy of the biological feature.
- **Interpretation phase**: This phase comprises of interpretation and structuring of the acquired and analyzed data. Mapping of function-biological feature-structure-structural strategy takes place in this phase.

All three phases of the process entail a manual effort, involving tasks such as search, acquisition, analysis, and curation. The gathered data is then stored in an open-source database using an interactive web-based data visualization tool. The primary sources for data acquisition are research articles and case studies related to biologically inspired structures, sourced from reputable outlets like Scopus, Google Scholar, as well as special issues and journals focused on bio-inspired design. It's worth noting that some bio-inspired case studies may not provide all the necessary information required for the construction of BIKAS. For instance, detailed descriptions of the structure and its corresponding structural strategies (specific configuration of the structure) may be lacking. In such instances, additional articles pertaining to the biological system are further researched and analyzed to supplement the construction process. Table 3.1 depicts the mapping of the embodiment function of biological features to its integrated structure and its structural strategy.

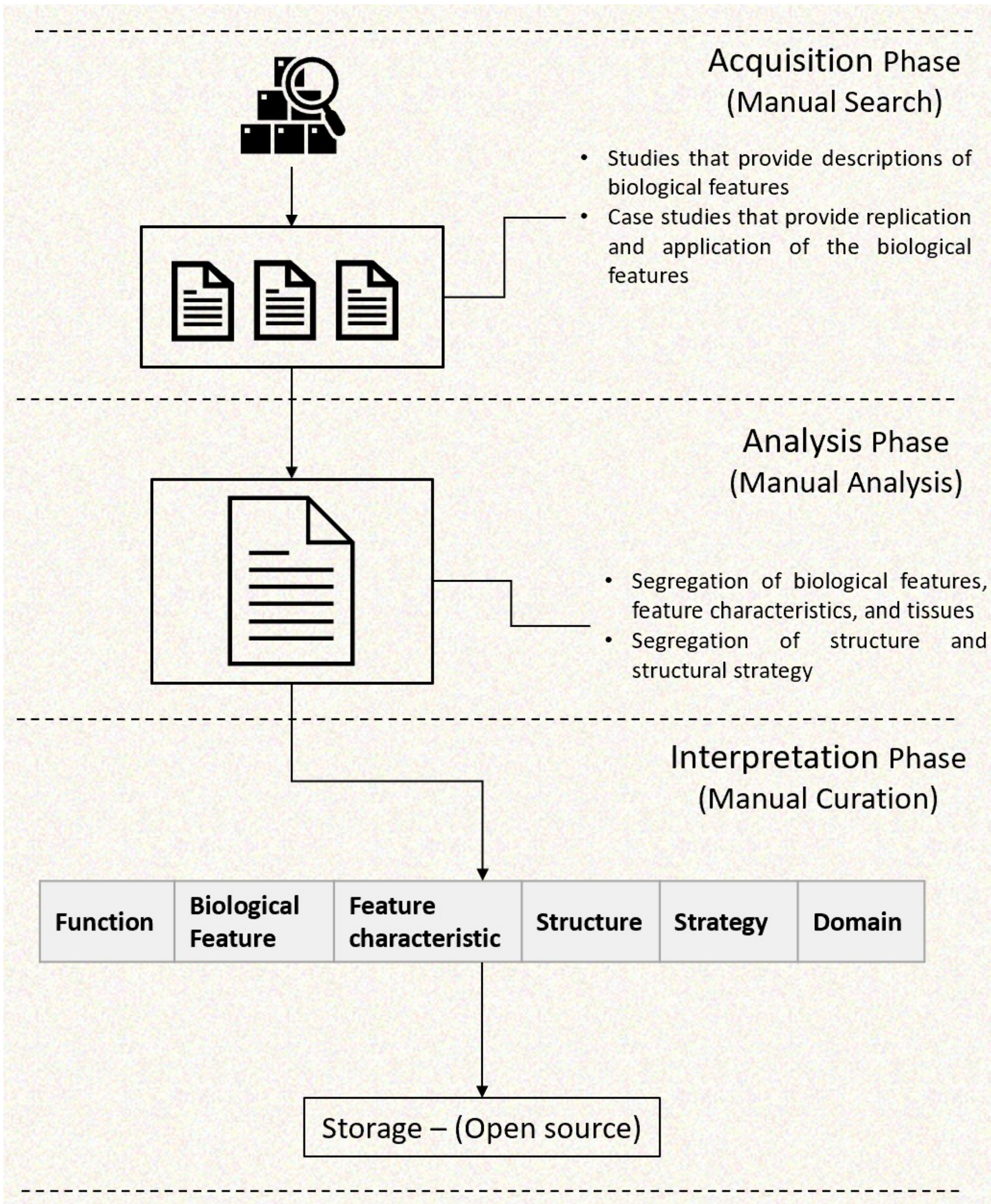

Figure 3.4: Construction flowchart of BIKAS

Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Repel water droplets	**Micro/Nano projections (Lotus leaf)**: Microstructures with a wax layer. The Microstructures are often pointed in shape [7]	***(Arrangement)*** The random arrangement of micro perturbances [77]
Repel water droplets	**Micro/Nano projections (Rose petal)**: Micro bumps in spherical shape [81]	***(Packing)*** Rosa CV. Showtime has low adhesion because of the densely packed microbumps [81]
Repel water droplets	**Micro/Nano projections (Butterfly Wings)**: Nano-tips on microstructures [14]	***(Arrangement and Orientation)***The directional hierarchical arrangement. Wings are tilted downwards [14]
Repel water droplets	**Micro/Nano projections (Silver ragwort)**: Hierarchical micro and nanostructure fibres are made up of unicellular and multicellular structures arising from epidermal tissues [82]	***(Arrangement)***The surface is covered by many random arrangement of fibres of a diameter of 6 micrometres [82]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Repel water droplets	**Micro/Nano projections (Rice Leaf)**: Hierarchical micro-papillae with epicuticular wax and longitudinal grooves [83]	***(Orientation)*** angle of inclination of the leaf [83]
Repel water droplets	**Micro/Nano projections (Cicada Wings)**: Cuticle contains an array of conical protuberances covered with a hydrophobic wax layer hexagonally arranged [84]	***(Arrangement and Orientation)***The hexagonal arrangement of spherical capped protuberances and the insect always stays in an upright position [84]
Repel water droplets	**Hair (Water Strider)**: Each leg is covered by an array of inclined, tapered hairs of conical shape, where each hair further has longitudinal and quasi-helicoidal nano grooves which enhance the water repulsion [85, 86]	***(Orientation and Arrangement)*** Inclined and tapered hair and Titled and randomly arranged micro-hair [87]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Repel water droplets	**Micro/Nano projections (Nepenthes)**: Crescent-shaped microstructure in the slippery zone and lunate-shaped microstructure present downward the slippery zone [88]	***(Orientation and Arrangement)*** microstructure oriented downward and irregular or randomly arranged microstructure [88]
Repel water	**Micro/Nano projections (Mosquito eyes)**: Ommatidia: micro hemispherical structure with nano papillae on the structure. [89]	***(Arrangement and Packing)*** Microscales hemispherical microphthalmos, on which nanoscale papillae are evenly arranged and tightly packed [89]
Repel micro-scale droplets	**Micro/Nano projections (Mosquito eyes)**: Mosquito Ommatidia (micro hemispherical structure). The hexagonal non-close packed (hcp) nano nipples on the microstructure trap air cushion surface [77]	***(Arrangement and Packing)*** A compact hexagonal non-close packed (hcp) arrangement with triangular voids of less than 3 micrometres. Tight packing of protrusions surface [77]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Adhere to a surface	**Hair (Gecko Feet)**: Nanofiber hair (Setae), Hierarchical arrangement of lamellae, setae stalks, and spatula tips [90]	***(Packing and Orientation)*** Close packed and branched setae [91]; Sticks when pulled from the palm towards the tip of the toe [90]
Adhere to an inclined surface	**Micro/Nano projections (Rose petals)**: Round and grooved fine structure on the plump. Micron-scale nubs (epidermis) of the rose petal surface [92]	***(Orientation)*** The geometry of sub-micron scale cuticular folding forms. The round and grooved fine Structure is oriented downwards from the nubs of the petal surface [92]
Adhere to an inclined surface	**Micro/Nano projections (Butterfly wings)**: Flexible nano-tips on ridging nano-stripes and micro-scales [14]	***(Arrangement and Orientation)*** Direction-dependent arrangement when wings are tilted upwards [14]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Resistance to wear and Resistance to abrasion	**Scales (Borrowing Pangolin)**: Overlapping Triangular scales and Corrugations present on each scale [93]	***(Packing, Arrangement and Orientation)*** Outward projection and overlapping of Pangolin scales [94] and the direction of the corrugation is parallel to the direction in which a pangolin dig [93]
Resistance to biofouling	**Placoid Scales (Sharkskin)**: The microstructure of sharkskin has a V-shaped micro-trench structure [95]	***(Packing and Arrangement)*** Overlapping and dense stacking of scales; Different shark species have a slightly different microstructure [95]
Resist erosion	**Micro/Nano projections (Desert scorpion)**: Grooves, and micro bumps on the surface can improve the anti-erosion performance [15]	***(Arrangement)*** The Random arrangement of the micro bumps [15]
Resist Shear	**Tiles (Ray Fish)**: Surface tiles [29]	***(Arrangement)***The periodic arrangement of surface tiles [29]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Resist compression	**Outer plate (Mantis shrimp - dactyl club)**: Uniaxial chitin proteins and nanofibers stacked along a helical twist in a periodic region [96]	***(Arrangement)*** Arrangement of nanofibers stacked along a helical twist in the periodic region in between the impact region and trained region [96]
Resist compression	**Outer shell (Abalone)**: Surface tiles with an outer prismatic layer and inner nacreous layer [97]	***(Arrangement)*** The periodic arrangement of stacked Voronoi palates in a brick-mortar arrangement with an organic matrix in between [97]
Resist retraction and Ease insertion	**Micro/Nano projections (Porcupine)**: Micro-triangular shaped barbs [20]	***(Arrangement)*** Sequentially arranged and the tip of barbs oriented towards the body [20]
Resist impact	**Skull (Woodpecker)**: Hyoid bone and Carnial bone containing hierarchical composite Structure [98]	***(Arrangement and Orientation)*** Hierarchical composite structure sandwiched between spongy bone [99]; Orientation of the skull to absorb impact [100]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Resist compression	**Skeletal Body (Venus flower basket)**: Hierarchical nested tessellation [29]	***(Hierarchical-overlaid)*** Arrangement of corner vertices nested across faces; Hierarchical-overlaid [29]
Resist compression and impact	**Peel (Pomelo)**: Porous nested Structure [101]	***(Stochastic-Voronoi)***Arrangement of dense vascular bundles surrounded by porous nested structure [101]; Stochastic-Voronoi [102]
Resist bending	**Leaves-cross section (cattail)**: Gradual varying I-beam sections with high-density foam at the bottom [103, 104]	***(Symmetry)*** Symmetry of the I-beam cross section along the axis
Resist bending	**Leaves-cross section (Iris)**: A sandwich panel containing two fiber-reinforced layers separated by low-density foam [104]	***(Symmetry)*** Symmetry of low-density foam placed in between two reinforced layers along the axis
Resist bending	**Leaf(Amazon Waterlily)**: Hierarchical branched cellular Structure [29]	***(Hierarchical-Branching)*** Edges defined by branching pattern [29]; Hierarchical-Branching

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Resist bending and Absorb energy	**Beak-cross section (Toucan and hornbill)**: Rod-like trabeculae foam sandwiched between hard outer shells made up of beta keratin tiles [105]	***(Asymmetry)*** Asymmetric lower and upper beak shape [105]
Reduce aerodynamic and fluidic drag	**Placoid Scales (Sharkskin)**: Hierarchical placoid microscale arrangement [5]; Sharkskin scales are made of enamels, combined with sharp spines and a rectangular base plate which goes deep inside the skin [5]	***(Skin stimulus and Orientation)***Shark scales are flexible and might erect passively [5]; The direction of the scales is parallel to the swimming direction [5]
Reduce aerodynamic and fluidic drag	**Micro/Nano projections (Dolphin)**: Presence of micro-rigids on the skin [106]	***(Skin stimulus)*** Dolphins can control their muscle to change their skin compliance [106]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Reduce Noise	**Feather serrations (Owl)**: Comb-like feathers and serrations at the leading-edge of the wing and fringe-like feathers at the trailing edge of the wing [107] and velvet-like surface of the wing [108]	***(Arrangement)*** Combination of leading edge serrations and surface ridges [107]; Arrangement of neighboring feather vanes that are merged by the fringes on the trailing edge of other feathers [109]
Reduce friction	**Micro/Nano projections (Pitcher plant)**: Microstructure (cresent shaped) on the peristome section of the plant. Microstructure (Cresent shaped) formation due to overlapping epidermal cells [110]	***(Orientation)*** It becomes extremely slippery when it becomes wet. The direction of the epidermis microstructure (cresent shaped) is directed inwards [110]
Reduce rupture or puncture	**Beak-cross section (Kingfisher beak)**: Rotational parabolic cross-section [18, 111]	***(Symmetry)*** Symmetry of the structure cross-section along the axis of the beak [111]
Reduce weight	**Skull (Bird)**: A sandwich structure where the inner core is made up of trabeculae foam [104]	***(Orientation)*** Trabeculae foam oriented perpendicular to the outer shell [104]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Reduce weight and Resist compression	**Cuttle Bone (Cuttlefish)**: Wall-septa arrangement with high porosity [112]	***(Periodic Tessellations)*** Wall-septa hierarchical arrangement [112]; Periodic-Wall septa [113]
Reduce drag	**Overall shape (Penguin)**: Spindle shape and formation of microbubbles due to feathers on the surface [106]	***(Symmetry)*** Symmetry of the body contour along the axis
Reduce drag	**Overall shape (Boxfish)**: Symmetrical box-shaped Structure [28, 114]	***(Symmetry)*** Symmetry of the body contour along the axis
Absorb energy, absorb water, and Filter water	**Skeletal Body (Luffa sponge)**: The fibrous network structure of the vascular system [115]	***(Hierarchical- nested)*** Regular oriented pattern but different in different sponge regions, namely outer, inner, inter, and core [115]; Hierarchical-nested arrangement [116]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Absorb energy	**Elytra forewing (Beetle)**: Pillar-like structure (chitin protein) between lower and upper skin (Honeycomb cells) [96]	***(Hierarchical Tessellations)*** Trabeculae at the intersection of honeycombs on lower and upper skin and chitin fibers on trabeculae arranged in linear or spiral manner [96]
Absorb energy	**Overall shape (Diatom)**: The transverse corrugated structure along the body [117]	***(Symmetry)*** Symmetry of the body contour along the axis
Absorb energy	**Stem-cross section (Bamboo)**: Vascular bundle that contains a multi-cell structure with gradient distribution [32]	***(Symmetry)*** Symmetry of vascular structural cross section along the axis
Absorb energy	**Leaves-cross section (Horsetail)**: Hollow vascular multi-cell structure [32]	***(Symmetry)*** Symmetry of vascular structural cross section along the axis

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Absorb energy	**Tree trunk-cross section (Palm tree)**: Multi-cell structure with cone-shaped columns and nodes. The individual cell takes the shape of a tetragon or pentagon [32]	***(Symmetry)*** Symmetrical cross-section along the axis
Absorb energy	**The shape of the body part (Coconut trunk)**: Conical Corrugated structure [32]	***(Symmetry)*** Symmetry of the conical corrugations and the cross-section along the axis
Absorb energy	**Overall shape (Balanus)**: Conical shape [32]	***(Symmetry)*** Symmetry of the conical along the axis
Absorb energy	**Outer shell (Conch)**: Three hierarchical lamellar macro layers (outer, middle, and inner) [104]	***(Orientation)*** Orientation of the cross-lamellar layers (Outer, middle and inner) [104]
Absorb energy	**Outer shell (Nacre)**: Voronoi tablet structures [32]	***(Packing)*** Dense Stacking [32]; An increase in the vonorosity of the tablets dissipates more energy [118]

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Absorb energy	**Outer shell (Crab)**: Helicoidal shape of meso layers in the shell [119]; Chitin is present in Mollusc shells of crabs [120]	***(Orientation)*** Helicoidal structure in complete 180 degrees rotation of the Bouligand layer [119]
Absorb energy	**Scales (Fish)**: Flexible and overlapping scales [32]; Scales of different geometries namely, Placoid, Ganoid, cycloid, and Ctenoid [121]	***(Arrangement and Orientation)*** Overlapping arrangement of Fish scales [32]; For example, the hard outer layer (mineral), middle soft layer (organic), and last layer with thin orthogonal collagen fiber [122]
Absorb water	**Micro/Nano projections (Namib desert beetle)**: Microstructural bumps on the surface of the beetle. Peaks are hydrophilic, and valleys are hydrophobic [123]	***(Orientation)*** Fog-basking. The beetle assumes a constant angle of 23 degrees. The angle is necessary for the fog drops to strike the surface and to collect dew of fog water by gravity [123]
Promote interlock	**Shape of the body part (Insect claws)**: Claw structure [124]	***(Asymmetry)*** Asymmetry of the claw structure along the axis

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Table 3.1: Mapping of the Meta-level Embodiment function, to the Biological features, its integrated structure, and its structural strategy (Continued)

Meta-level embodiment function	**Biological feature and its Integrated Structure**	**Structural Strategy**
Manage variable friction	**Scales (Snakeskin)**: Microstructure (triangular) on the central ventral and side ventral scales. The scales form the epidermis layer of the snakeskin [21]	***(Arrangement)*** Longitudinal pits and caudal elevations of the triangular microstructure [125]; Anisotropic nature of microstructure [21]

3.4.1 Evaluation Criteria of BIKAS

The effectiveness of qualitative databases involving analogical transfer, such as utilizing biological data for engineering design, relies on a thorough understanding of the biological data [126]. In the case of knowledge databases for bio-inspired design that exclusively employ representations of biological features, the assessment is based on the degree to which biological information is abstracted and comprehended, as well as how effectively it is utilized in constructing a solution. Two specific modes of biological representation have undergone evaluation: SAPPhIRE [126] and S-B-F (Structure-Behaviour-Function) [127]. The assessment involves a comparative study between the SAPPhIRE representation of biological information and a more generic text-image representation, conducted through a series of questionnaires administered to designers [126]. Similarly, a comparative study comparing the S-B-F representation with text-only and text-graphic-tabular representations was carried out using questionnaires [127]. Table 3.2 outlines the evaluation criteria for assessing repositories dedicated to bio-inspired design. Notably, these modes of representation lack associated methods, and repositories without such methods are evaluated through comparative studies.

Table 3.2: Evaluation Criteria of repositories for bio-inspired design

Mode of Representation (Biological information)	**Associated method**	**Approach**	**Procedure**
SAPPhIRE	Not Applicable	Comparison between modes of representation	Questionnaire
S-B-F	Not Applicable	Comparison between modes of representation	Questionnaire

BIKAS is a distinctive biological information database, representing a unique mapping encompassing function, feature, structure, and structural strategy. The embodiment-level abstraction of various biological features supports the development of new methods for the generation of multifunctional conceptual and early-stage embodiment designs. BIKAS is a manually curated knowledge database exploring and representing the intricate details including the configuration of complex structures that are essential for developing multifunctional products. The following Chapter 4, discusses a detailed design method for developing multifunctional early-stage embodiment-level designs.

Unlike existing system-level abstraction techniques, the creation of the BIKAS knowledge database marks an initial step toward representing the functions exhibited by biological features as a combination of integrated structure and structural strategy. Additionally, abstracting biological features at the granular level and mapping functions, features, feature characteristics, structure, and structural strategy is essential for designers to grasp during the emulation process. Furthermore, the BIKAS knowledge data serves as an initial source for Machine Learning (ML) algorithms to extract biological features from various data sources and cluster them based on their function, features, and characteristics. This process leads to the classification of biological features into their respective geometric designations, termed Domains. The database will be an open source. Moreover, it allows the users to populate the database. Web development frameworks such as Flask or Django will be used for developing the database.

The efficacy of this intricate mapping and classification of biological features is demonstrated through the creation of distinctive bio-inspired multi-functional early-stage embodiment product concepts, which are subsequently validated using computer simulations. Numerous case studies have been published to assess the effectiveness of the knowledge database and the associated method. The case studies are presented in chapter 7.

3.5 Summary

The embodiment-level abstraction technique plays a pivotal role in streamlining the complex system-level abstraction processes currently in use. Presently, system-level abstraction focuses on overall function, as well as material, energy, and signal flow between different components. Biological features often exhibit multi-scaled functions. For instance, the superhydrophobicity of a lotus leaf results from the amalgamation and arrangement of micro and nanostructural components. Describing the physical structure at the embodiment level necessitates an abstraction technique capable of detailing the feature's structure and configuration.

BIKAS is a knowledge database that encompasses over 50 biological systems abstracted at the embodiment level, emphasizing the exhibited functions through a combination of integrated multi-scale structures and structural arrangements. Additionally, integrating BIKAS with current system-level abstraction techniques allows for a holistic view of biological systems.

Part III

Method for Multifunctional BID

4

Domain Integrated Design (DID)

Most of the existing design methods that support multifunctional concept development achieve a multifunctional design based on the functional decomposition principle. However, they do not have a classification and mapping mechanism to categorize functional biological features based on their geometrical significance. Methods such as Function-Means have a classification mechanism that categorizes the biological features as energy delivery, energy regulatory, and auxiliary devices. This chapter discusses in detail the method developed that categorizes the functional biological features based on their characteristics, and geometrical significance. Furthermore, mapping the categorized geometric features to their respective tissues of origin. Figure 4.1 depicts the overview of the design methods for multifunctional bio-inspired designs and the DID method developed based on the case-based classification and mapping of biological features presented in this chapter. The contents of this chapter have been reported in Designs journal [41] and [13]

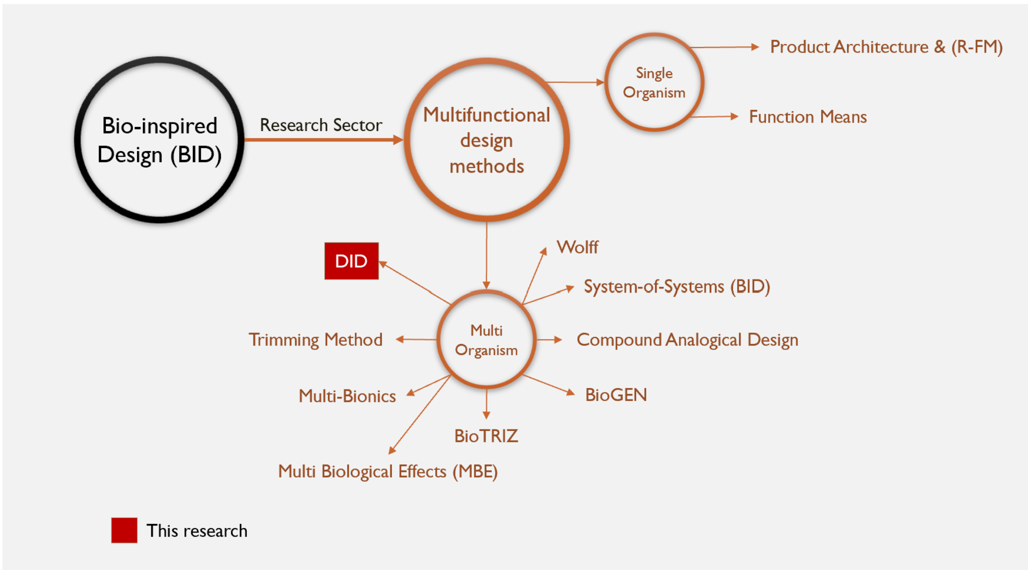

Figure 4.1: Overview of the existing multifunctional bio-inspired design methods and the newly developed DID method.

4.1 Case-based classification and Mapping

Classifying and mapping biological features based on their characteristics is carried out step-by-step. As depicted in Figure 4.2, the initial step involves categorizing biological features by their characteristics into their respective domains designated by their geometric definitions. Subsequently, the second step entails associating these biological features with their corresponding plant and animal tissues. These biological features encompass observable morphological and anatomical traits found in both the animal and plant kingdoms. The characteristic of a biological feature denotes its visual appearance, discernible form, or physical attributes. For example, in the case of a shark's riblet, the biological feature characteristic would be the texture of its body or skin. Similarly, a shell serves as a biological feature characteristic of the protective surface of a mollusk. The biological features and their associated functions are derived from an analysis of approximately 50 case studies in bio-inspired design, as detailed in Chapter 3 of this thesis. The classification of these biological features based on their characteristic traits is further elucidated through the application of a classification framework. The subsequent section outlines the methodology employed for classifying these

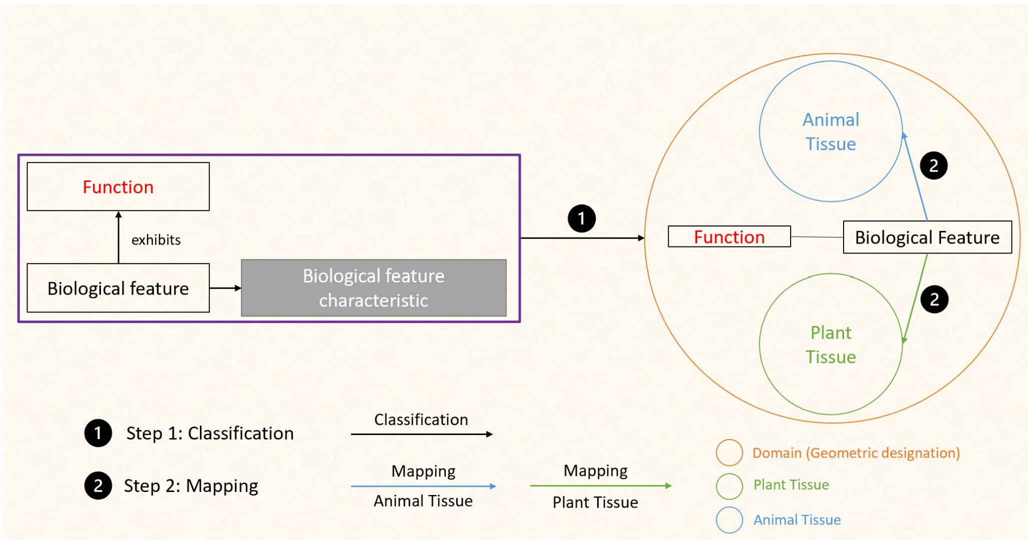

Figure 4.2: Classification and mapping schematic of biological features.

biological features into their respective domains.

Mapping of biological features by its characteristics into Domains

The following describes the classification of features to their domains. Figure 4.3 provides a schematic of the classification technique.

- Biological characteristics that serve specific functions, like body textures (such as skin, scales, fur, or wool) and protective elements such as hard outer covers (like shells, plates, or tiles), fall within the surface domain. For instance, this includes features like the water-repellent nature of tiny projections on a lotus leaf [7] and the durability of scales on a burrowing pangolin [94]

- Biological functionalities characterized by porous prismatic and foam structures arranged in diverse tessellated patterns—periodic, stochastic, and hierarchical—encompass features like periodic tessellations with unary, binary, ternary, or quaternary connections, stochastic tessellations with Poisson distribution, Voronoi, or crystal growth patterns. Additionally, hierarchical tessellations exhibit branching, nested, or overlaid connections [29] and are categorized within the cellular-structure domain. For instance, this includes the energy absorption function observed in the hierarchical tessellations of a beetle's elytra forewing [96]

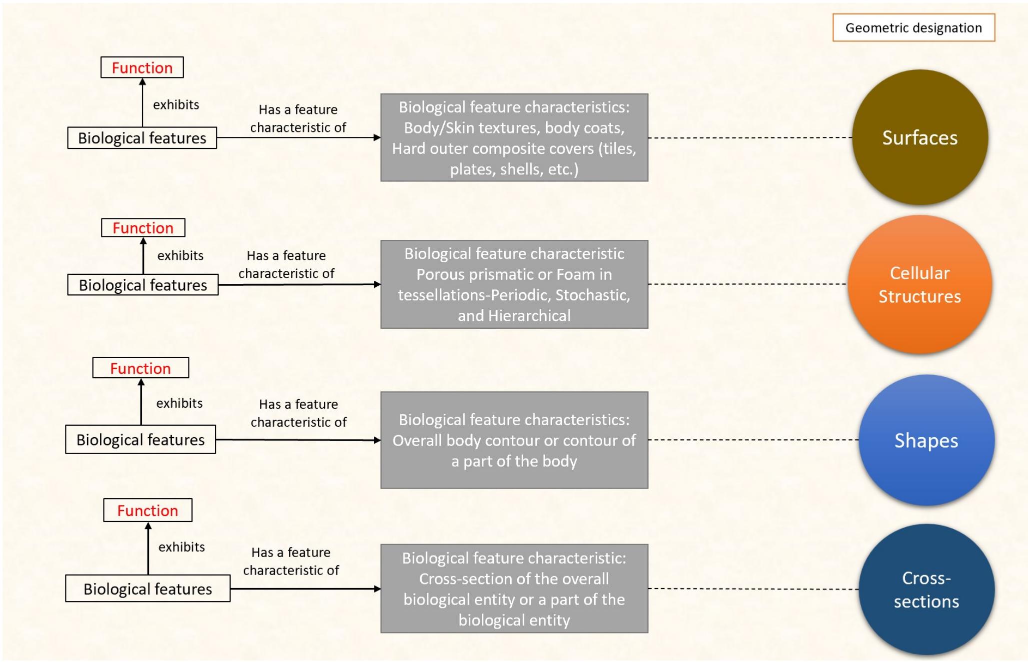

Figure 4.3: Classification framework of biological features.

- When a biological function stems from characteristics like the complete body contour of a biological system or the contour of a specific body part, it falls within the shape domain. For instance, this classification encompasses the drag-reducing function facilitated by the overall shape of the boxfish's body [28]

- When a biological function arises from features like the cross-section of a biological system or a part thereof, it falls under the cross-section domain. For example, this includes the capacity to reduce rupture facilitated by the rotational parabolic cross-section of the kingfisher's beak [18, 111]

Domains

The classification of biological features into their respective geometrical designations brings us to the formal definitions of Domains.

- *Domains* represent different biological features performing various functions with a common geometric designation. Furthermore, each biological feature is mapped to the respective tissue from which they originate.

The formal definitions of each of the **Domain** is as follows:

- *Surface*: Textures found on the body or skin, scales, body coats (like wool, hair, scales, etc.), and elements such as hard outer composite covers (such as shells, plates, and tiles) fall within the surface domain.
- *Cellular Structures*: Structures composed of porous prismatic and foam arrangements, organized into diverse tessellated patterns including periodic, stochastic, and hierarchical designs. These encompass various characteristics like periodic tessellations featuring unary, binary, ternary, or quaternary connections; stochastic tessellations employing Poisson distribution, Voronoi, or crystal growth patterns; and hierarchical tessellations involving branching, nested, or overlaid connections.
- *Shapes*: The complete shape (entire body contour) of a biological system or the shape of a specific part of the biological system (like the contour of a body part) is categorized within the shape domain.
- *Cross-sections*: The cross-section of the biological system or cross-section of a part of the biological system

The sub-domains within cellular structures and surfaces encompass Shapes and Cross-sections. These sub-domains operate based on a synthesis of diverse biological traits or a fusion of various biological tissues. Each sub-domain, whether it pertains to cross-section or shape, is associated with a distinctive biological feature that pertains to either the surface or the cellular structure. Table 4.1 shows the mapping of the biological feature to its biological feature characteristics

Table 4.1: Mapping of Biological feature, to its characteristics

Biological fetaures	**Biological feature characteristics**
Micro/Nano projections (Lotus leaf)	Body/Skin texture (Plant)
Micro/Nano projections (Rose petal)	Body/Skin texture (Plants)
Micro/Nano projections (Butterfly Wings)	Body/Skin texture (Animals)

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Table 4.1: Mapping of Biological feature, to its characteristics (Continued)

Biological fetaures	**Biological feature characteristics**
Micro/Nano projections (Silver ragwort)	Body/Skin texture (Animals)
Micro/Nano projections (Rice Leaf)	Body/Skin texture (Plants)
Micro/Nano projections (Cicada Wings)	Body/Skin texture (Animals)
Hair (Water Strider)	Body coat (Animals)
Micro/Nano projections (Nepenthes)	Body/Skin texture (Plants)
Micro/Nano projections (Mosquito Eyes)	Body/Skin texture (Animals)
Hair (Gecko Feet)	Body coats (Animals)
Micro/Nano projections (Rose petals)	Body/Skin texture (Plants)
Scales (Borrowing Pangolin)	Body/Skin texture (Animals)
Placoid Scales (Sharkskin)	Scales (Animals)
Micro/Nano projections (Desert scorpion)	Body/Skin texture (Animals)
Tiles (Ray Fish)	Hard outer cover Tiles (Animals)
Outer plate (Mantis shrimp - dactyl club)	Hard outer cover Plates (Animals)
Outer shell (Abalone)	Hard outer cover Shell (Animals)
Micro/Nano projections (Porcupine)	Body coat or Modified hair (Animals)
Skull (Woodpecker)	Sandwich Shell (Animals)
Skeletal Body (Venus flower basket)	Hierarchical tessellation (Plants)

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Table 4.1: Mapping of Biological feature, to its characteristics (Continued)

Biological fetaures	**Biological feature characteristics**
Peel (Pomelo)	Stochastic tessellation (Plants)
Leaves-cross section (cattail)	Cross-section of the body part (leaves)
Leaves-cross section (Iris)	Cross-section of the body part (Stochastic tessellation: Vascular bundles)
Leaf (Amazon Waterlily)	Hierarchical tessellation (Plants)
Beak-cross section (Toucan and hornbill)	Cross-section of the body part (Outer composite plate and inner stochastic tessellation: spongy bone)
Micro/Nano projections (Dolphin)	Body/Skin texture (Animals)
Feather serrations (Owl)	Body coats (Animals)
Micro/Nano projections (Pitcher plant)	Body/Skin texture (Plants)
Beak-cross section (Kingfisher beak)	Cross-section of the body part(Outer plate and Stochastic tessellation)
Skull (Bird)	Sandwich Shell (Animals)
Cuttle Bone (Cuttlefish)	Periodic tessellation (Animals)
Overall shape (Penguin)	Full body contour (Animals)
Overall shape (Boxfish)	Full body contour (Animals)

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Table 4.1: Mapping of Biological feature, to its characteristics (Continued)

Biological fetaures	**Biological feature characteristics**
Skeletal Body (Luffa sponge)	Hierarchical tessellation (Plants)
Elytra forewing (Beetle)	Hierarchical tessellation (Animals)
Overall shape (Diatom)	Full body contour (Animals)
Stem-cross section (Bamboo)	Cross-section of the body part (Stochastic tessellation of gradient pores: Vascular bundles)
Leaves-cross section (Horsetail)	Cross-section of the body part (Stochastic tessellation)
Tree trunk-cross section (Palm tree)	Cross-section of the body part (Stochastic tessellation of gradient pores: Vascular bundles)
The shape of the body part (Coconut trunk)	Body part contour (trunk) (Plants)
Overall shape (Balanus)	Full body contour (Animals)
Outer shell (Conch)	Hard outer cover Shell (Animals)
Outer shell (Nacre)	Hard outer cover Shell (Animals)
Outer shell (Crab)	Hard outer cover Shell (Animals)
Scales (Fish)	Scales (Animals)

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Table 4.1: Mapping of Biological feature, to its characteristics (Continued)

Biological fetaures	**Biological feature characteristics**
Micro/Nano projections (Namib desert beetle)	Body/Skin texture (Animals)
Shape of the body part (Insect claws)	Body part contour (Claw) (Animals)
Scales (Snakeskin)	Body/Skin texture (Animals)

Mapping of Biological features to the Tissues

Understanding the principles of the biological world is essential for accurately associating biological features with their respective tissues. This section delves into the structural hierarchy of biological systems and elucidates the roles played by tissues in both animal and plant kingdoms. Marshall's study [128] identified three key factors influencing cell structure and shape: inheritance from the mother cell, protein-protein interactions, and the self-assembly process. Once a specific structure is achieved, similar cells come together to form a tissue with a specific function. Groups of tissues then combine to create an organ, and organs, in turn, unite to constitute an entire organism [129]. The following is a concise overview of the types and functions of plant and animal tissues, as gleaned from the literature on plant anatomy [130] and animal anatomy [131]. Plant tissues can be broadly classified into four categories: meristematic tissues, simple permanent tissues, complex permanent tissues, and epidermis.

- Meristematic tissues play a crucial role in the growth of plants, primarily located at the tips of both roots and stems.

- Simple permanent tissues function in the storage of food and energy. This category encompasses parenchyma, collenchyma, chlorenchyma, aerenchyma, and sclerenchyma, each with its specific role.

- Complex permanent tissues are responsible for the transportation of food and water, also known as vascular tissues. They are formed by a combination of different cell types. The most common examples of complex permanent tissues include xylem and phloem.

- Epidermal tissue serves to protect plants from the external environment. It consists of a single layer of continuous cells. Examples of epidermal features include hair-like structures on 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.

- Connective tissue plays a vital role in providing structural support and framework. This includes dense connective tissue for bone connections, areolar tissue for skin-to-muscle connections, and skeletal tissue for overall framework. Adipose tissue aids in absorbing mechanical shocks, while fluidic tissue primarily contains red blood cells (RBC) for oxygen transport and white blood cells (WBC) for immune system maintenance.

- Muscular tissue is responsible for facilitating movement and locomotion. It encompasses skeletal, smooth, and cardiac muscles.

- Epithelial and epidermal tissues primarily serve the function of protection and defense. Epithelial tissue acts as a protective layer for internal organs.

- Nervous tissue facilitates the transmission of information from all parts of the body to the brain and vice versa.

Deriving inspiration from natural systems serves as a catalyst for generating innovative product concepts [132]. This process involves contemplating various levels of abstraction within a biological system and understanding its functional interactions. Additionally, the integration of components from diverse biological systems hinges on comprehension of biological and natural materials [133]. This distinctive classification and mapping approach effectively bridges the divide between biology and technology, thereby significantly streamlining the process of conceptual design. Notably, the characteristics observed in biological systems predominantly stem from adaptations developed at the tissue level.

Mapping biological features to their corresponding tissues provides product designers with enhanced insights into both structural attributes and material properties. This reciprocal understanding between biological features

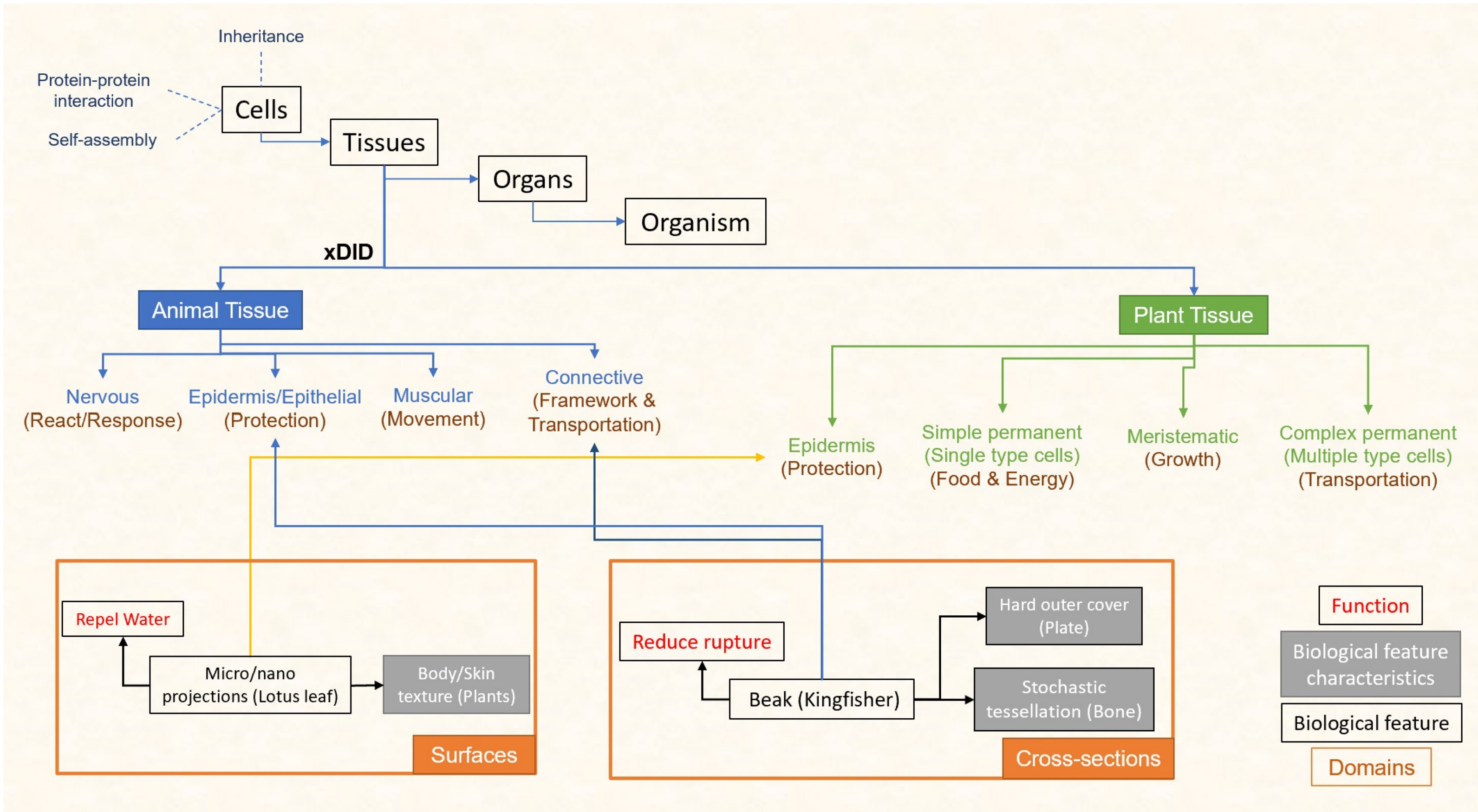

Figure 4.4: Network Map showing the classification of different biological features to their respective geometric designations.

and material characteristics proves invaluable. In Figure 4.4 a comprehensive network map is presented, classifying biological feature characteristics into domains and aligning them with their respective tissues as developed in this study. As depicted in Figure 4.4, within the surface domain, the lotus leaf's micro/nano projections employ its epidermal tissue to repel water droplets [134]. Conversely, snakes utilize scales on their skin to achieve effective friction in rugged terrains, a feature mapped to epidermis/epithelial tissue [135]. Similarly, in the cross-section domain, the kingfisher's beak structure, characterized by a rotational parabolic shape that reduces the risk of rupture, is attributed to the connective tissue (beak bone) and epidermal tissue (keratinous layer) [19]. This reduction in rupture/puncture is achieved through the synergistic combination of connective and epidermal tissues. Table 4.2 shows the mapping of the biological features to the tissues from which they originate.

Table 4.2: Mapping of Biological feature to the Tissues from which they originate

Biological feature	**Meta-level embodiment function**	**Tissue**
Micro/Nano projections (Lotus leaf)	Repel water droplets	Epidermal tissue (Micro-papillae and epicuticular wax) [134, 136, 137]
Micro/Nano projections (Rose petals)	Repel water droplets	Epidermal tissue (Micro-papillae and epicuticular wax) [136–138]
Micro/Nano projections (Silver ragwort)	Repel water droplets	Epidermal tissue [82]

Continued on next page

Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	Meta-level embodiment function	Tissue
Micro/Nano projections (Rice leaves)	Repel water droplets	Epidermal tissue (Micro-papillae and epicuticular wax [136, 137, 139]
Micro/Nano projections (Cicada wings)	Repel water droplets	Epidermal tissue (epidermal structures) [140]
Micro Hair (Water Strider)	Repel water droplets	Microtrichia (epidermal cells) [141]
Micro/Nano projections (Nepenthes)	Repel water droplets	Epicuticular wax and epidermal cells [142]
Hair (Gecko Feet)	Adhere to Surface	Epidermal tissue (Setae) [143]
Micro/Nano projections (Butterfly wings)	Adhere to an inclined surface	Epidermis (wing scales) [144]
Micro/Nano projections (Mosquito Eyes)	Repel micro-scale droplets	2D Epithelium and 3D Ommatidium [145]
Scales (Borrowing Pangolin)	Resistance to wear and Resistance to abrasion	Keratinous scales [146]
Placoid Scales (Sharkskin)	Resistance to biofouling and reduce aerodynamic and fluidic drag	Dermal denticles (Dentine) [147]
Micro/Nano projections (Dolphin)	Reduce aerodynamic and fluidic drag	Dermal papillae and epidermal ridges [148]

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Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	**Meta-level embodiment function**	**Tissue**
Feather serrations (Owl)	Reduce Noise	Keratin structural proteins/Keratinous material [135, 149]
Scales (Snakeskin)	Manage variable friction	Epidermis (Keratin layers) [135]
Micro/Nano projections (Desert scorpion)	Resist erosion	Chitinous cuticle [150]; Cuticle (Extracellular matrix by epidermis) [151]
Scales (Fish)	Absorb energy	Dermal scales (epidermal cells) [152]
Micro/Nano projections (Pitcher plant)	Reduce friction	Epidermal tissue [110, 142]
Micro/Nano projections (Namib desert beetle)	Absorb water	Epicuticle and Epidermis [123]
Tiles (Ray Fish)	Resist Shear	Tesserae (Cartilage) [153]
Outer shell (Crab)	Absorb energy	Mollusc Shell (Calcareous exoskeleton) [154]
Outer shell (Conch)	Absorb energy	Mollusc Shell (Calcareous exoskeleton) [154, 155]

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Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	**Meta-level embodiment function**	**Tissue**
Outer shell (Nacre)	Absorb energy	Mollusc Shell (Calcareous); Aragonite layer and Beta-Chitin [154, 156]
Outer plate (Mantis shrimp - dactyl club)	Resist compression	Calcareous exoskeleton [157]
Outer shell (Abalone)	Resist compression	Mollusc Shell (Calcareous exoskeleton) [154]
Micro/Nano projections (Porcupine)	Resist retraction and Ease insertion	Keratins [158]
Skull (Woodpecker)	Resist impact	Hard outer shell and bone (Connective tissue) [159, 160]
Skull (Bird)	Reduce weight	Sandwich of External hardcover and trabeculae (Connective Tissue) [161]
Skeletal Body (Luffa sponge)	Absorb energy, absorb water, and Filter water	Xylem and Phloem (Vascular bundles) [115, 162]
Elytra forewing (Beetle)	Absorb energy	Honeycomb Trabeculae (Connective tissue) [163]

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Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	Meta-level embodiment function	Tissue
Skeletal Body (Venus flower basket)	Resist compression	Silica-based cylindrical skeletons [164]
Peel (Pomelo)	Resist compression and impact	Vascular bundles and Parenchymatic tissue [165]
Cuttle Bone (Cuttlefish)	Reduce weight and Resist compression	Dorsal shield and lamellar matrix (Aragonite and Beta Chitin) [166]
Leaf (Amazon Waterlily)	Resist bending	Xylem and Phloem [162]
Overall shape (Penguin)	Reduce drag	Body skeleton and Muscles (Connective and Muscular tissues) [106]
Overall shape (Boxfish)	Reduce drag	Body skeleton-Carapace and collagen fibres (Connective tissue) [167] and Muscular Tissue
Overall shape (Diatom)	Absorb energy	Siliceous cytoskeleton (Frustules) [117, 168]
Shape of the body part (Coconut trunk)	Absorb energy	Cork [169]; Vascular tissue [170]; Vascular Cambium [171]

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Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	Meta-level embodiment function	Tissue
Overall shape (Balanus)	Absorb energy	Combination of parietal and longitudinal canal tissue [172]
Shape of the body part (Insect claws)	Promote interlock	Keratin structural proteins/Keratinous material [135]
Cross-section of the body part (Kingfisher beak)	Reduce rupture or puncture	Sandwich structure of keratin and bony layer (Connective) [173]
Cross-section of the body part (Toucan and hornbill beaks)	Resist bending and Absorb energy	Exterior keratin and fibrous bony network (trabeculae) [19]
Cross-section of the body part (Bamboo stem)	Absorb energy	Vascular cambium; Xylem and Phloem [32, 162]
Cross-section of the body part (Horsetail leaves)	Absorb energy	Vascular bundle, endodermis and Sclerenchyma [32, 174]
Cross-section of the body part (palm tree trunk)	Absorb energy	Cork cellular material [169]; Vascular tissue [170]; Vascular Cambium [171]
Cross-section of the body part (cattail leaves)	Resist bending	Vascular cambium; Xylem and Phloem [175]

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Table 4.2: Mapping of Biological feature to the Tissues from which they originate (Continued)

Biological feature	**Meta-level embodiment function**	**Tissue**
Cross-section of the body part (Iris leaves)	Resist bending	Sclerenchyma [176]

4.2 Illustrations of classification, mapping, and construction of Domains

A comprehensive categorization and mapping mechanism has been intricately developed. Below is a recap accompanied by a visual representation that illustrates domains encompassing biological features. These domains encompass biological features with identical feature characteristics and are linked to their corresponding tissues. The intricate mapping system provides a clear and concise overview, facilitating a deeper understanding of the intricate relationships between biological features and their geometry within the given domains.

Surfaces: The surface domain encompasses biological features characterized in Section 4.1. The tissues associated with this domain, as classified thus far, include the epidermal and epithelial tissues found in both plant and animal kingdoms, as well as enamels that extend the epidermal tissue and surface layers formed through molecular self-assembly. Additionally, it encompasses external structural features formed by connective tissues in the animal kingdom. Notable examples within this domain comprise the epidermal tissue in lotus leaves [134], enamel in sharkskin [5], variously oriented surface layers in conch shells [96], and keratinous structures [135]. Figure 4.5provides a schematic representation of the classification of biological features and their characteristics into domains, along with the mapping of these features to their respective biological tissues. As illustrated in Figure 4.5, the superhydrophobic property of the lotus leaf is attributed to its integrated structure, specifically its micro/nano projections. This biological feature characteristic pertains to body/skin texture and is categorized within the surface domain, mapped to the epidermal tissue in the plant kingdom. Similarly, snakeskin achieves effective friction management through its scales [21], a biological

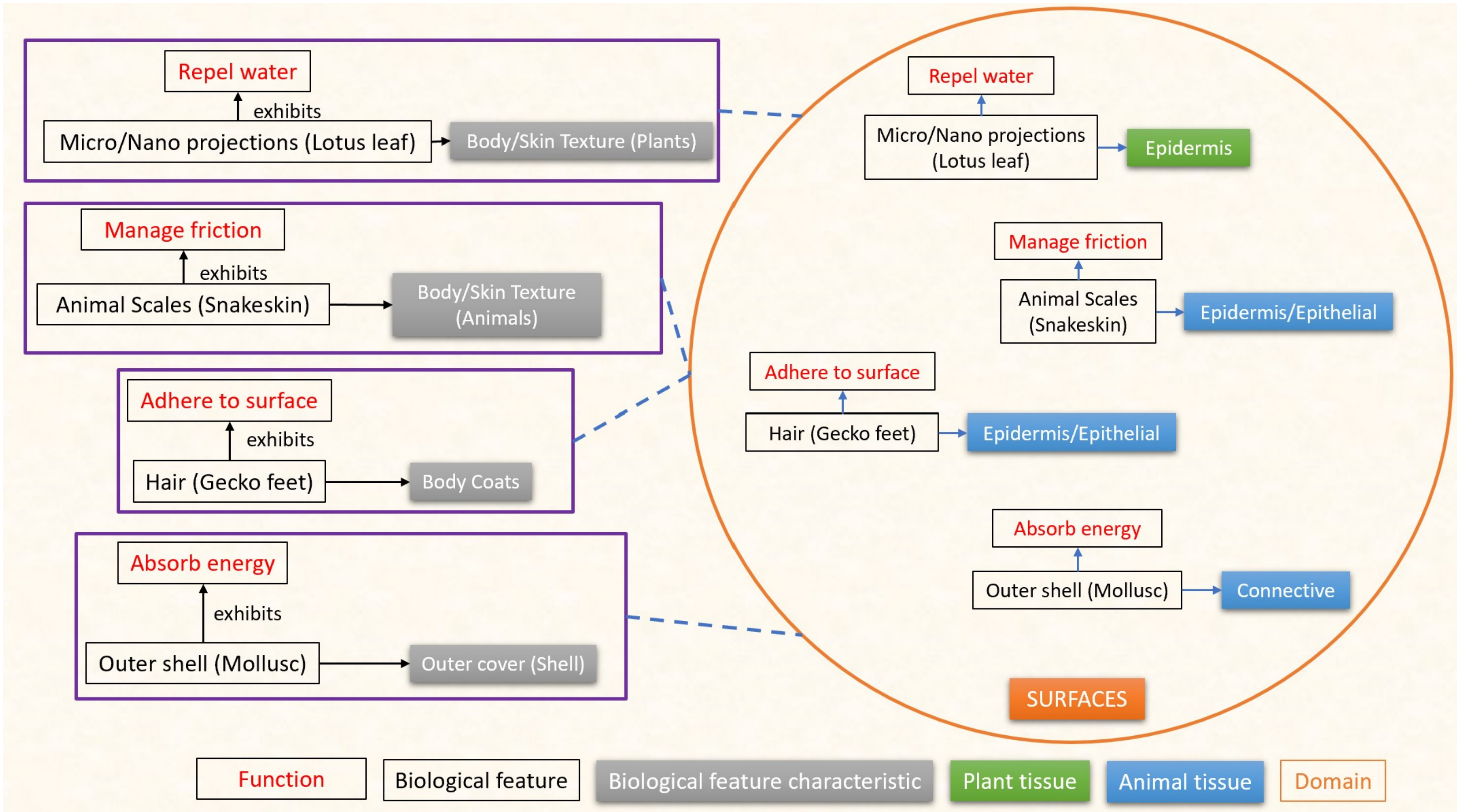


Figure 4.5: Pictorial representation of the overview of categorization and mapping in surfaces domain.

feature characterized by body/skin texture, which falls under the surface domain and is mapped to the epidermis tissue in the animal kingdom [135]. Likewise, the mollusk shell's energy absorption capability is attributed to its outer shell [32], characterized by a hard outer cover. This feature is classified within the surface domain and mapped to connective tissue [154]. Finally, the gecko's adhesive ability to surfaces is attributed to its hair [135], a biological feature with a characteristic body coat. This falls under the surface domain and is mapped to the epidermal tissue in the animal kingdom [143].

Cellular structure: This domain encompasses biological features and their associated characteristics detailed in Section 4.1. The tissues associated with this domain, as classified thus far, include the simple permanent tissue in the plant kingdom and connective tissue from the animal kingdom. Figure 4.6 provides a schematic representation that categorizes biological features by their characteristics into domains and maps these features to their corresponding tissues. As depicted in Figure 4.6, waterlily leaves demonstrate resistance to bending, attributed to their biological feature—the leaf. The biological characteristic, hierarchical tessellation, refers to the branching of the stem [29]. Waterlily leaves are classified as cellular structures and are mapped to the simple permanent tissue in the plant kingdom, specifically sclerenchyma, which provides mechanical support to the plant body [162]. Similarly, the pomelo peel exhibits resistance to impact due to its biological feature—the peel, and possesses a biological characteristic of stochastic tessellation [101]. The pomelo peel is classified as a cellular structure and is mapped to the simple permanent tissue in the plant kingdom [165].

In both the cross-section and shape sub-domains, the exhibited function arises from a combination of distinct biological characteristics or a fusion of various biological tissues. These sub-domains, focusing on cross-sectional attributes and overall shape, encompass specific biological feature characteristics that can pertain to either the surface or the cellular structure. Below are detailed definitions and explanations of these sub-domains, accompanied by a schematic illustration that demonstrates their classification and the corresponding mapping to their respective tissues

Cross-sections: The cross-section domain encompasses biological features with characteristics detailed in Section 4.1. Specifically, cross-sections are defined as the shape obtained by the intersection of a solid body with a three-dimensional plane. The tissues associated with this domain, as classified thus far, include meristematic tissue, complex permanent tissue, and simple permanent tissue from the plant kingdom, along with connective tis-

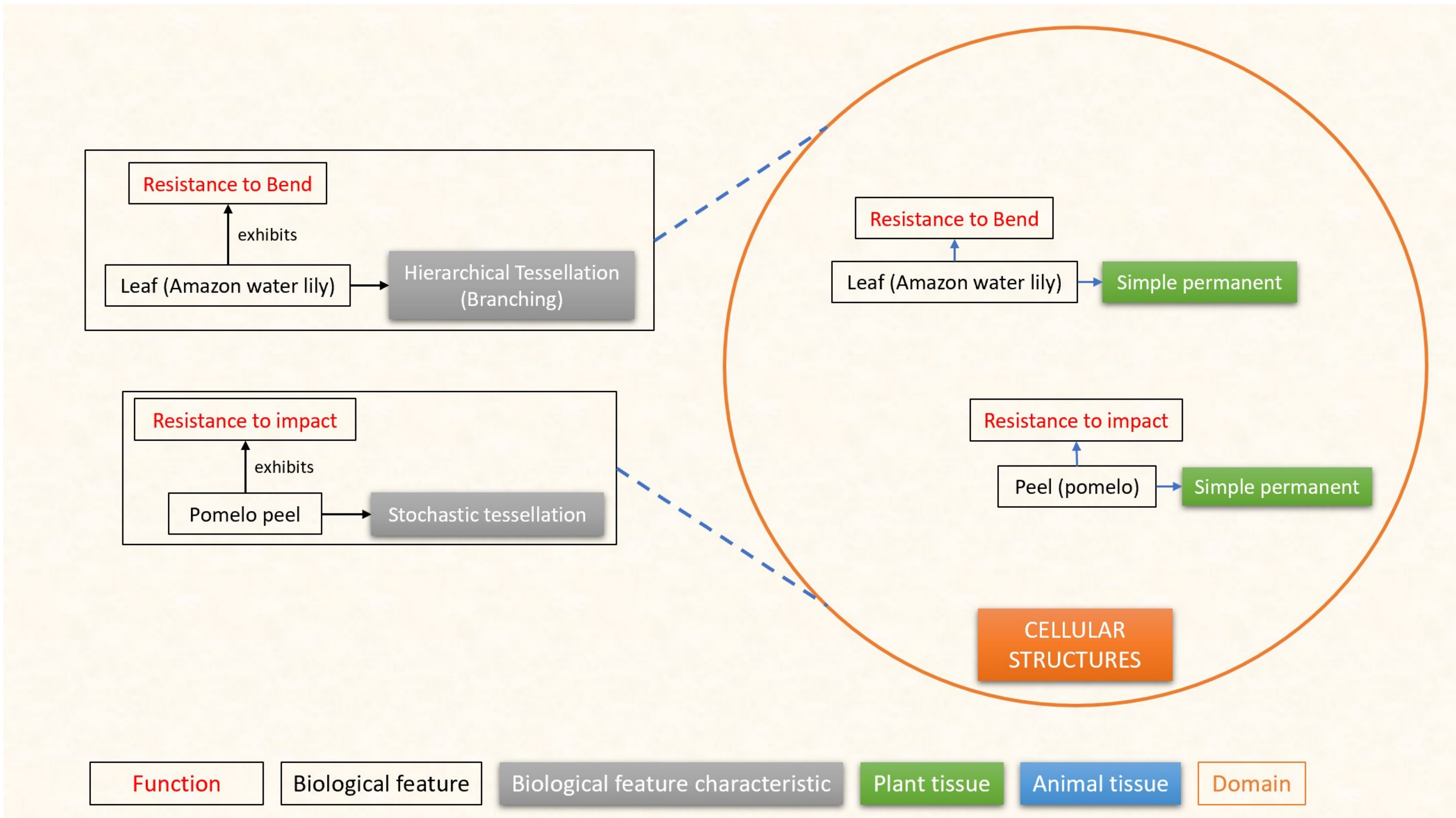


Figure 4.6: Pictorial representation of the overview of categorization and mapping in cellular structures domain.

sue from the animal kingdom. Figure 4.7 offers a schematic representation that categorizes biological features and their characteristics into the cross-section domain, illustrating the corresponding mapping to their respective tissues. As demonstrated in Figure 4.7, the bamboo tree stem's cross-section features the capacity to absorb energy [32] through a combination of biological tissues, namely simple permanent, complex permanent, and meristematic tissue. The stem's cross-section is categorized within the cross-section domain due to its characteristic biological feature—a cross-sectional view of the body parts. The vascular stochastic foam structure is formed through the amalgamation of meristematic, simple, and complex permanent tissues [162].

Similarly, the kingfisher's beak exhibits a reduction in puncture force due to its distinctive biological feature—the rotational parabolic cross-section [18, 111]. This reduction in puncture force is achieved through the combination of biological feature characteristics, including plates and foamy bone. The kingfisher's beak cross-section is classified within the cross-section domain, with the biological feature characteristic of the hard outer plate mapped to epidermis/epithelial tissue in the animal kingdom, while the inner bone is mapped to connective tissue [173].

Shapes: The shape domain encompasses biological features with characteristics detailed in Section 4.1. These features may include meristematic tissue from the plant kingdom, as well as muscular and connective tissue from the animal kingdom. Shapes can be mathematically defined, often exhibiting symmetrical properties, which can further be categorized into axial, bilateral, and radial symmetry [177]. Additionally, shapes can also display asymmetry, as seen in basking sharks, which alter their jaw geometry to an asymmetric form for efficient fish-catching with minimal energy expenditure [78]. As illustrated in Figure 4.8 the schematic classification of the shape domain. The penguin's spindle-shaped overall form achieves a reduced drag function [106], characterized by a full body contour as its biological feature. This body shape, however, results from the combination of muscular and connective tissues [106]. The biological features and their associated characteristics are mapped to muscular and connective tissues in the animal kingdom.

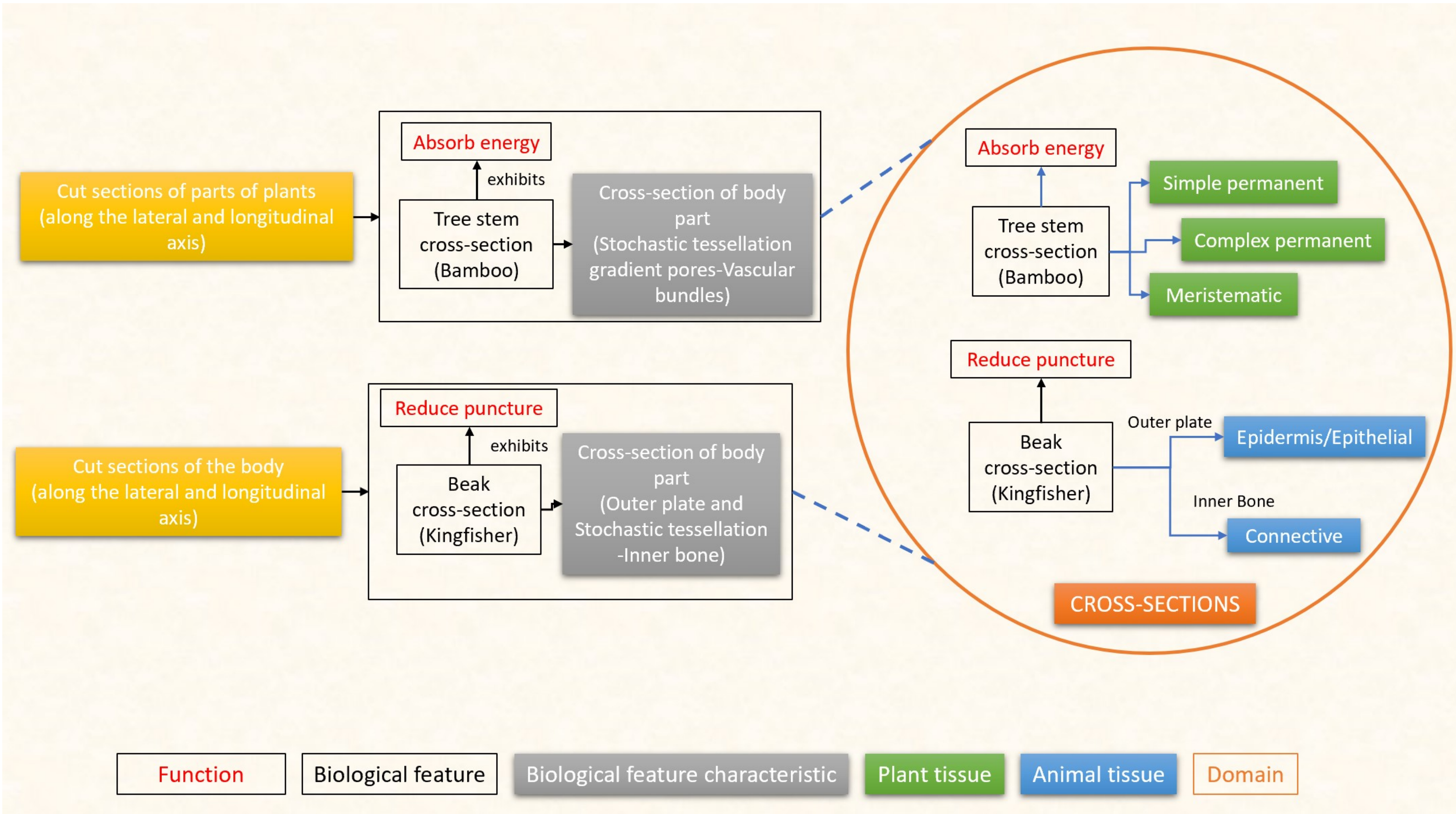


Figure 4.7: Pictorial representation of the overview of categorization and mapping in cross-sections sub-domain.

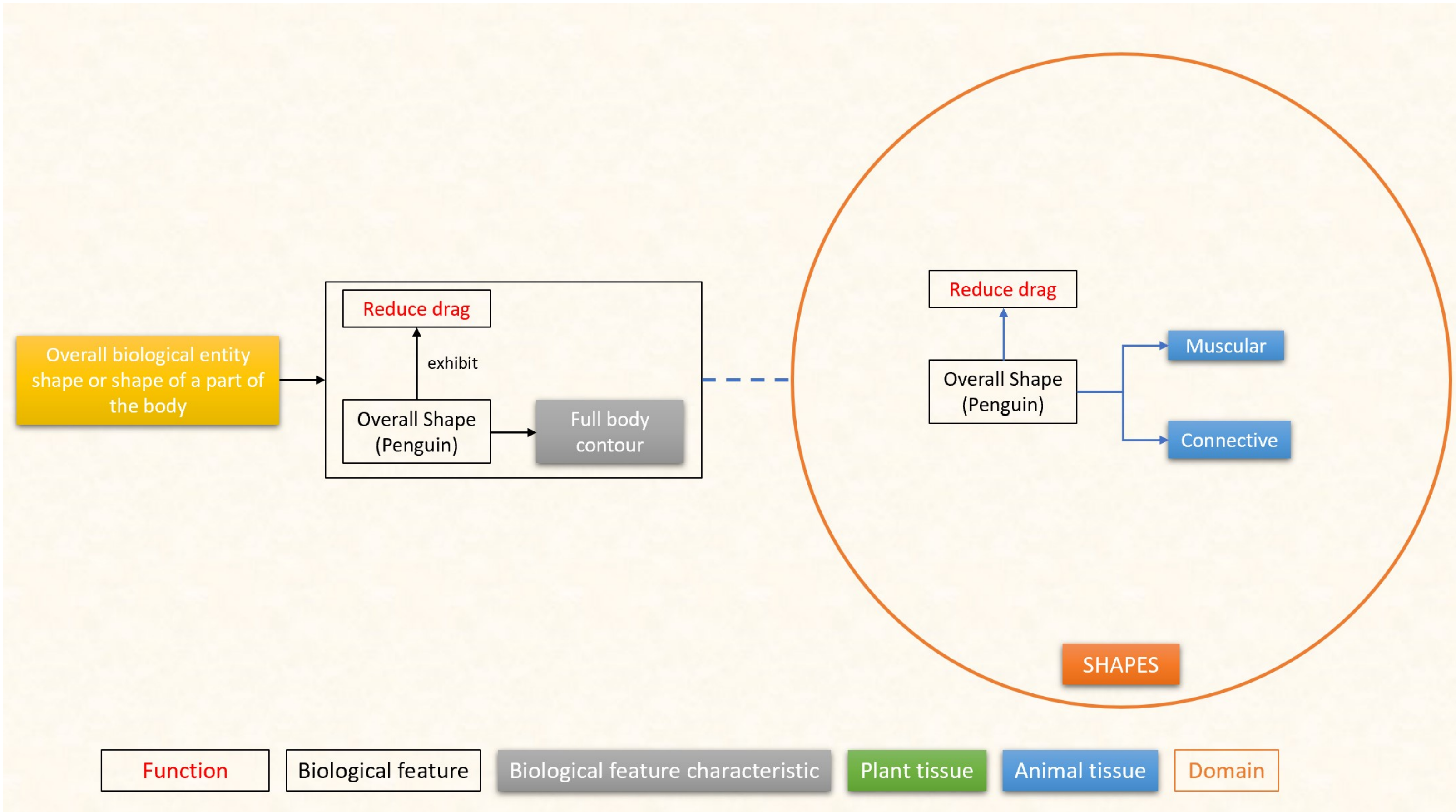


Figure 4.8: Pictorial representation of the overview of categorization and mapping in shapes sub-domain. Picture from [13]

4.3 Extension of DID: Expandable Domain Integrated Design (xDID)

The classification of biological features based on their characteristics is a complex undertaking, as the current set of domains may not encompass every conceivable biological feature. This section details the extension of the DID classification system by introducing new domains and micro-domains. The contents of this section are reported in Designs Journal [13]. More details of the xDID model are presented in Chapter 6

4.3.1 Extension of Domains

The sheer diversity of biological features presents a significant challenge in categorizing them into predefined domains. However, the xDID addresses this complexity by introducing additional domains and establishing micro-domains within the same category. These micro-domains provide more precise descriptions and classifications of biological features based on their characteristics. For instance, as illustrated in Figure 4.9, the micro-domain for surfaces encompasses outer composite tiles, outer composite plates, and outer composite shells, which possess intricate composite structures. Similarly, the micro-domains for cellular structures are categorized by the type of connection in the tessellations, such as beam-based or face-based connections. The cross-section sub-domain pertains to cross-sections formed through composition or by sandwiching two or more distinct structures, such as a combination of outer plates with internal muscular and bone structures. The introduction of micro-domains serves the purpose of enriching the idea-generation process.

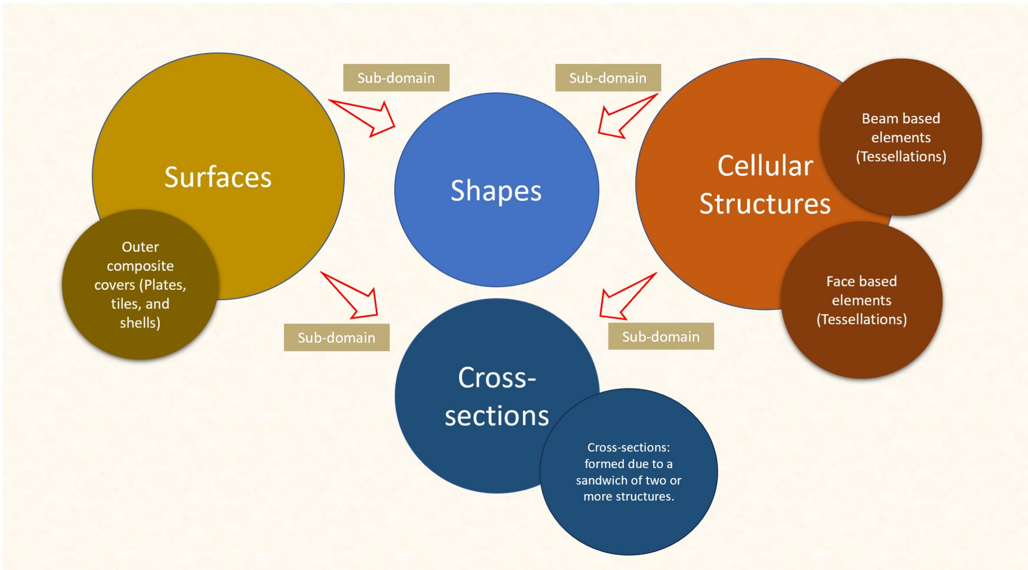


Figure 4.9: Schematic showing the micro-domains emerging from the defined domains to accommodate complex biological features that do not fit in the current definitions.

4.4 Summary

Current methods aiding in the creation of multifunctional conceptual designs typically rely on function decomposition, breaking down functions into sub-functions and integrating solutions for each to generate multifunctional design concepts. Among these approaches, the Function-Means method uniquely categorizes biological features into energy delivery, regulation, support, and auxiliary devices. An alternative method, the Reduced Function-Means (RF-M) based product architecture, advocates employing a single structure to address multiple functions. However, this approach is limited to solving functions that can be simplified or combined, such as representing various functions of nacre's shell—like resisting bullet shots and knife strikes—as a single function, such as impact resistance.

To foster the amalgamation of uncommon functions and expedite the selection of biological features showcasing diverse functions for inspiring and generating multifunctional concepts at an early stage, a structured categorization of biological features is essential. Domain Integrated Design (DID) emerges as a method specifically developed to facilitate the swift and appropriate selection of biological systems based on their functions and geometric relevance. This method categorizes biological features into distinct geometric classifications known as 'Domains,' encompassing Surfaces, Cellular Structures, Shapes, and Cross-sections. Additionally, it involves mapping these categorized biological features back to their respective tissues of origin, initiating a search for materials that align well with the functional properties of these biological tissues. Currently, domains are not integrated into the BIKAS knowledge database. The comprehensive knowledge base of biological features, along with their classification into respective domains, will become available once the knowledge base is hosted as open-source software.

Part IV

Selection of relevant Biological Analogy

5

Meta-level Design Parameters

Throughout the acquisition and analysis of more than 50 biological features, a notable trend emerges: diverse biological organisms showcase similar functions through various features, sharing not only function but also comparable geometric relevance and scale. For instance, sharkskin [5] and dolphin skin [106] both aid in drag reduction, while the stochastic cellular structure of pomelo peel and woodpecker skull serves for impact resistance [99, 101].

In nature, diverse organisms independently evolve traits to serve similar purposes or fulfill common needs, known as convergent evolution. While current design methods have set criteria for selecting comparable biological features, there is a need for quantitative criteria to enable more precise selection based on geometric relevance and scale. The significance of meta-level design parameters lies in their ability to select between different geometries that serve the same function and belong to the same domain. For instance, as illustrated in Figure 5.1, meta-level design parameters can aid in choosing between sharkskin and dolphin skin, which fulfill the same function and belong to the same domain i.e. Surfaces. Similarly, between pomelo peel and woodpecker beak that fulfill the same function and belong to the same domain i.e. Cellular structures. These parameters are geometry-specific and mostly integrated into the BID process.

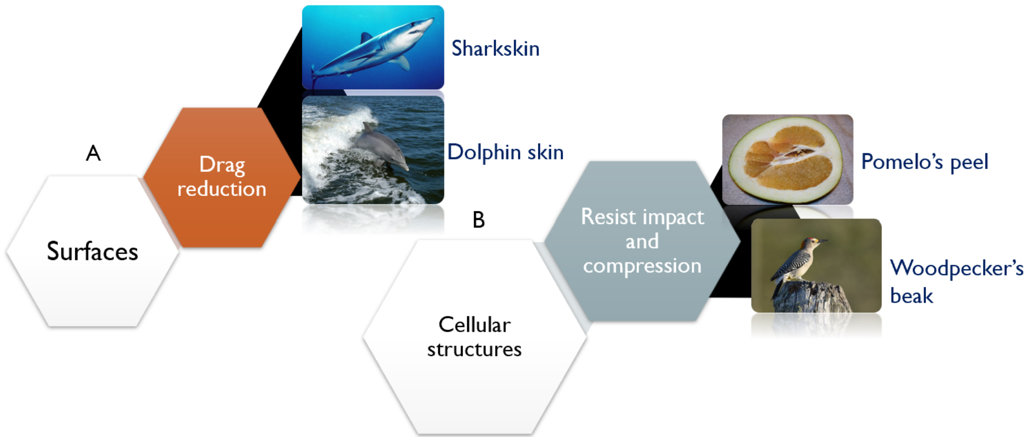


Figure 5.1: Depicting the significance of Meta-level design parameters A) to choose between Sharkskin and Dolphin Skin; B) to choose between pomelo peel and woodpecker's beak

This chapter undertakes a comparison of the total interaction areas between sharkskin and dolphin skin to determine the superior candidate for a drag-reducing structure. Such a comparative analysis between two distant biological features that serve similar functions establishes quantitative criteria that bio-inspired designers can use to select more accurate and suitable features. The proposed criteria that is the interaction area proves to be a crucial parameter in cases where a precise feature selection is required. This chapter validates the criteria proposed as meta-level design parameters by conducting computational fluid dynamic (CFD) simulations to compare drag force and coefficient of drag between sharkskin and dolphin skin. Moreover, this chapter showcases the application of meta-level design parameters in recently developed multifunctional bio-inspired design methods, such as the Domain Integrated Design (DID) method. The contents of this chapter are under review in the Bioinspiration and Biomimetics [178]. The meta-level design parameters are quantitative criteria developed in addition to the existing generic criteria that were utilized in various multifunctional design methods. The overview of the current criteria is depicted in Figure 5.2.

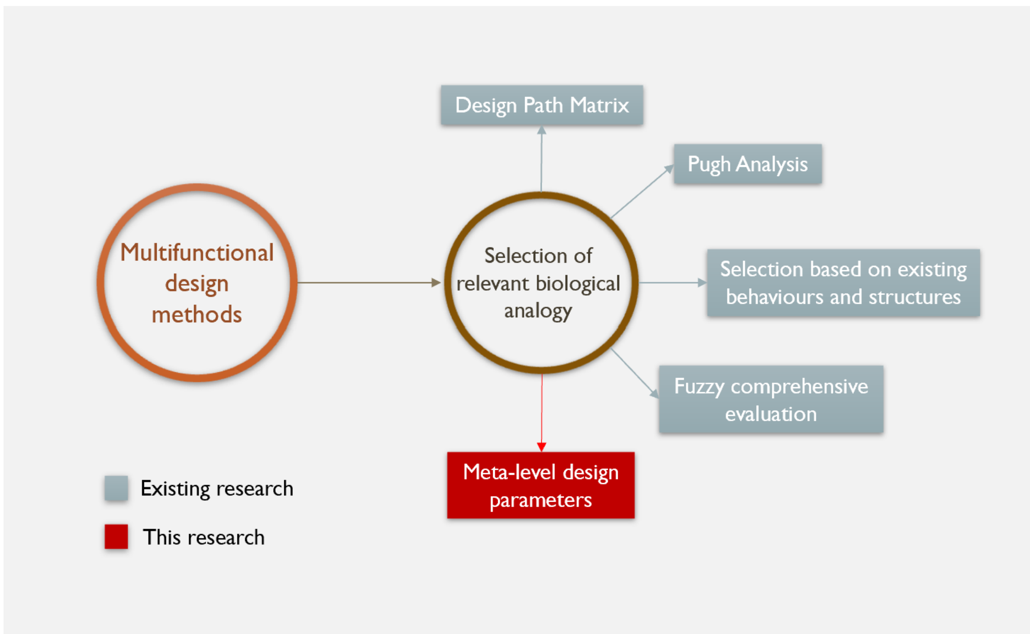


Figure 5.2: Overview of the existing criteria employed in the selection of relevant biological analogy and the quantitative meta-level design parameters that are employed in selection.

5.1 Current criteria for selection of relevant biological features

The literature has put forth criteria to tackle the challenge of choosing an appropriate biological analogy with similar functionality. Table 5.1 displays the evaluation criteria utilized in documented approaches for multifunctional Bio-inspired design.

Table 5.1: Criteria for the selection of biological analogy that exhibit the same function

Multifunctional bio-inspired design methods	**Selection/Evaluation criteria of biological systems**
BioGEN [62]	Design path Matrix (Challenges and Pinnacles) x 9 identified criteria
System-of-systems BID [66]	Pugh Analysis (Design requirements)
Reduced Function Means (RF-M) and Product Architecture [12]	Select behaviours that use existing behaviours, select structures that show multiple behaviours simultaneously and Choose structures that illustrate interactions with already existing structures
Trimming method [38]	Fuzzy comprehensive evaluation method (Compatibility, Completeness, and Feasibility)

However, there are no quantitative criteria that support the selection of a biological feature that exhibits the same function and has a similar geometric relevance and scale.

The BioGEN method, as outlined in reference [62], incorporates a set of nine defined criteria for evaluation. These criteria encompass aspects such as process, flow, adaptations, scale, environmental context, morphological, structural, material, and other features. The System-of-systems BID, described in reference [66], employs Pugh-Analysis as its selection process. This analysis technique is a multi-criteria decision-making tool where the criteria are determined based on design requirements. In contrast, the Reduced Function-Means (RF-M) method and the product architecture-based approach utilize a simplified function-means tree to represent biological similarities through interactions between structure, function, and behavior constructs. The criteria involve selecting behaviors that leverage existing ones, structures demonstrating multiple behaviors concurrently, and structures exhibiting interactions with existing ones. The function-sharing technique aims to choose features from an organism that fulfill multiple functions. In the case of the trimming method [38], the selection of a relevant biological analogy is carried out using fuzzy comprehensive evaluation criteria, assessing compatibility, completeness, and feasibility.

Furthermore, more specific parametric criteria are necessary to aid in the selection of a biological feature for emulation, particularly when features have similar geometric attributes and scale. These criteria enable a more precise selection during the conceptual and early stages of product development. To establish such parameters for selection, it is imperative to comprehend the underlying principles governing the formation of structural features in both plant and animal kingdoms. The subsequent section will present the analysis conducted in this research on the structural formation in biological systems. This analysis effort culminates in the proposal of meta-level design parameters as effective and detailed selection criteria for choosing biological features.

5.2 Structure formation in Biological organisms and Meta-level Design parameters

Figure 5.3 depicts the schematic of the process of structural formation of features observed in biological systems. As shown in Figure 5.3 cells of a particular type and shape combine to form tissues that perform various functions. The cell's shape, structure, and functioning are governed by mechanisms such as inheritance from the parent cell, self-organization or self-assembly, and protein-protein interactions with other cells [128]. The cell's shape is determined by inheritance, protein interactions, and the mechanisms that govern them. This research, however, focuses on investigating self-organization mechanisms to understand how cells organize themselves into tissues. Three types of proteins are responsible for the stability and structural support in the cells. The actin proteins are responsible for cell movements, locomotion, contraction of muscles, and cell division [179]. Likewise, the intermediate proteins provide architectural support to the cell [180]. Finally, the microtubule proteins are responsible for the distribution of cell organelles [181]. Figure 5.3 illustrates the critical role of protein folding in ensuring proper protein function. This folding process is influenced by factors such as ionic strength, presence of substances, pH, temperature, surface interactions, and modifications [182]. The fundamental organizing principle of cells into tissues is self-organization, a core concept in pattern formation across various physical, chemical, and biological systems [183]. Self-organization involves the spontaneous creation of coherent structures in both temporal and spatial dimensions within a system, arising from collaborative interactions among its components [183]. Cells, with their continuous energy consumption and diverse localized interactions among proteins, lipids, carbohydrates, and nucleic acids, provide an ideal environment for self-organization to occur [183]. This phenomenon can manifest through self-assembly, autonomous patterning, and self-propelled morphogenesis. For instance, muscle and cartilage regeneration has been achieved by promoting the self-organization of muscle cells [184]. The arrangement of cells (cellular packing) within a tissue is crucial for maintaining regularity, enabling communication, promoting growth, and providing structural support and material properties. Through patterning and interactions among lower-level components (such as cells) , self-organization gives rise to the emergence of an entire system [185]. Similarly, the self-assembly process involves the organized structural formation of building blocks, primarily through non-covalent bond interactions [186].

On the other hand, in crystal systems like the binary colloidal system, the shape of particles notably affects non-covalent bond formation [187]. The interacting surfaces of particles play a crucial role in minimizing total surface-free energy. Research on clathrate crystals emphasizes that the arrangement and orientation of molecules are critical factors in self-assembly to reduce surface free energy [188]. Despite these findings, no explicit parameter for the selection process has been defined in these studies. Even amidst difficulties, there's recognition of how interacting surfaces—like those between cells or particles—affect tissue and crystal structure formation. As a result, considering the interaction area as a higher-level design parameter becomes a conceivable approach. The selection criteria are based on the hypothesized meta-level design parameters are as follows:

- "For any multifunctional application, if one of the multifunction is described as an anti-adsorption/absorption or repulsion or reduction, select the features with a lower total interaction area for combination."

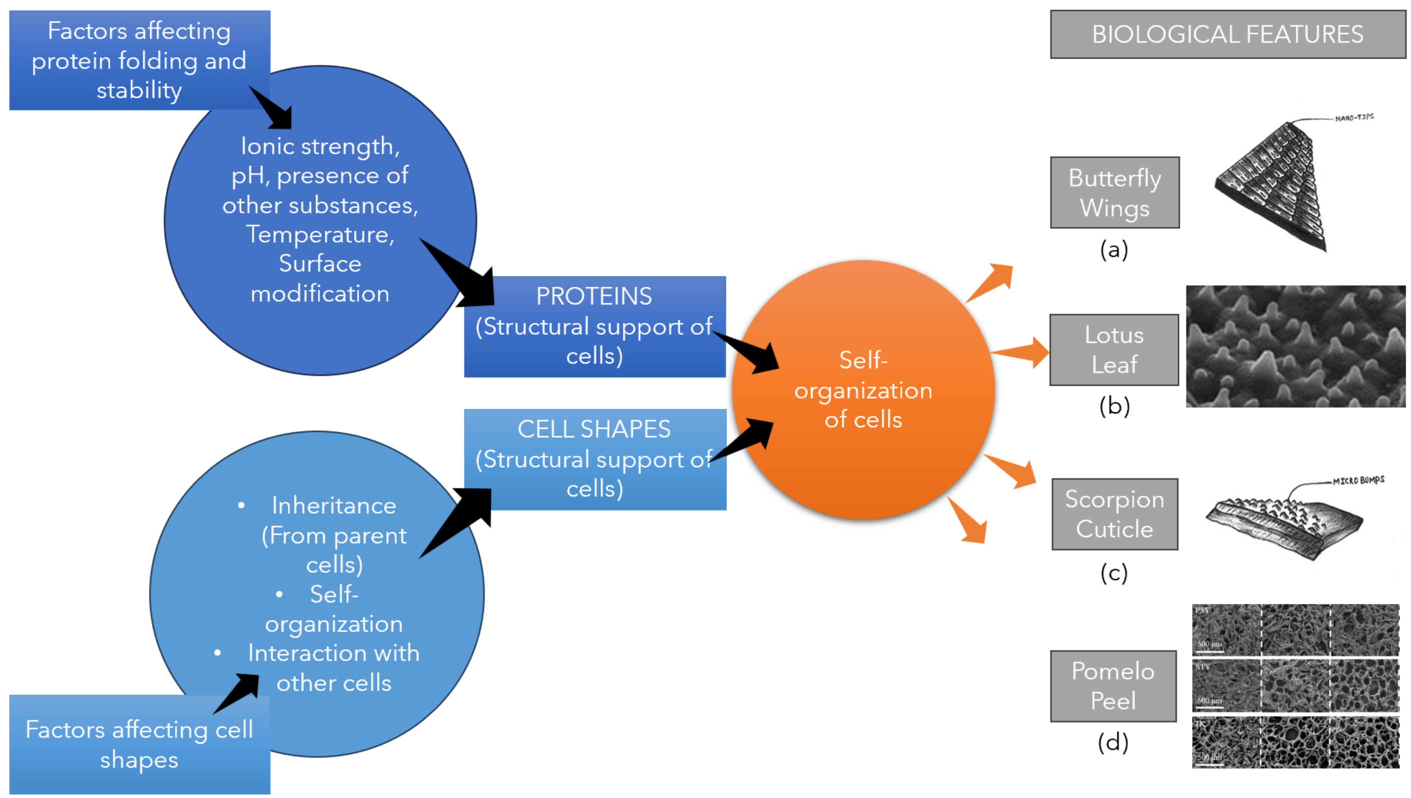


Figure 5.3: Formation of biological features such as a) butterfly wings [14], b) lotus leaves [7], c) scorpion skin [15], and d) pomelo peel [16] by the self-organization of cells.

- ”For any multifunctional application, if one of the multifunction can be described as adsorption/absorption or attraction, select the features with a higher interaction area for combination.”

Table 5.2 introduces the proposed meta-level design parameters that augment the criteria for selecting features based on function, geometry, and scale similarities. Meta-level design parameters enhance existing criteria for selecting suitable features based on function, geometrical relevance, and scale similarity. In the Surface domain, the interaction area of the biological feature is the designated parameter. Similarly, for the Cellular Structures domain, the interaction area and porosity are considered parameters. In the sub-domains of Shapes and Cross-Sections, the meta-level design parameter is the scale of the feature. Scales range from nano to meter scales, and the scale factor can be employed as a selection parameter based on specific design requirements. Currently, the scale parameter is suggested for the Cross-Sections and Shapes sub-domains.

Table 5.2: Meta-level Design Parameters

Domains	**Features**	**Meta-level Design Parameters**
Surfaces	Micro and Nano projections; Body Coats; Skin textures; Outer hard and sandwiched plates, tiles and shells	Interaction area
Cellular Structures	Prismatic, Stochastic, and Hierarchical tessellations	Interaction area; Porosity
Shapes	Overall Shape (Contour) or Shape of a part of the body	Scale
Cross-sections	Cross-section of the whole body or part of the body	Scale

The subsequent section elucidates the validation process for the proposed meta-level design parameters. Specifically, among the suggested parameters, the interaction area and porosity have undergone validation for the Cellular Structures Domain [189]. This validation is accomplished through a simulation focused on the multifunctional design of a non-pneumatic tire, drawing inspiration from the combination of snakeskin (from the Surfaces Domain) and features akin to Woodpecker's beak and Pomelo Peel (from the Cellular Structures Domain). The interaction area for the surface Domain is validated in this research through a case study on lightweight and drag-reducing structures. Furthermore, case studies will be carried out to continuously validate the parameters for sub-domains.

5.3 Validation of Meta-level Design parameters

To validate the interaction area as a parameter for the surface domain, a problem statement has been formulated: designing structures with reduced weight and drag for advanced undersea applications. The drag reduction function is conceptualized as liquid repulsion, where the skin's ability to delay vortex generation facilitates faster swimming in biological species [190]. Adopting a multifunctional design, the honeycomb prismatic structure is selected for its lightweight functionality from the Cellular Structures Domain. Two biological systems from the Surface Domain, sharkskin, and dolphin skin, exhibit similar drag-reduction functionality. A combination of two structures from two domains results in the generation of bio-inspired lightweight and drag-reducing structures.

Previous research on sharkskin's drag reduction explored factors such as scale spacing and pattern. Staggered-overlapped structures significantly improved swimming performance, while simplified riblet-like models failed to replicate the hydrodynamic environment under static conditions [191]. Sharkskin alters vortex structure and flow, increasing self-propelled swimming speed [191]. Another study indicated that the smallest denticles on sharkskin reduced drag and increased self-propelled speed, emphasizing the importance of replicating both rigid and flexible components for accuracy [192, 193].

Dolphins exhibit drag reduction through surface skin ridges and skin compliance. Compliant skins increase boundary layer thickness, delaying the transition from laminar to turbulent flow, while bulges on dolphin skin generate micro vortices, replacing sliding friction with rolling friction to reduce fluidic drag [194]. Studies on beluga and killer whales, belonging to the Dolphin species (Odontocetes), suggest that their skin alters the boundary layer for reduced drag during sprinting speeds [195]. Another study indicates that dolphins adjust skin elasticity by controlling muscle tension, blood pressure, or temperature, delaying flow transition [196]. Transverse sinusoidal grooves on dolphin skin trap vortices, creating a slip condition that contributes to turbulence augmentation in the boundary layer, reducing flow separation during pressure drag [197].

5.3.1 Design concept development

The research's case study commenced with product sketching, with Figure 5.4 a) conceptual sketch depicting the amalgamation of the Honeycomb structure and sharkskin scales, while Figure 5.4 b) showcases the combination of the honeycomb structure and Dolphin skin ridges. Notably, this case study relies solely on computer simulations, emphasizing the early-stage selection of suitable features in the product development process. Prototype validation is anticipated during later stages of product development [198]. Table 5.3, Table 5.4, and Table 5.5 outline the dimensions of the honeycomb adapted from Hailu and Biratu [199], dolphin skin adapted from Wainwright et al. [195], and sharkskin structures adapted from Luo et al. [5] respectively. Figure 5.5 depicts the CAD models of a unit of the honeycomb and dolphin skin-inspired lightweight and drag-reducing structure. Figure 5.6 depicts the CAD models of a unit of the honeycomb and Sharkskin-inspired lightweight and drag-reducing structure.

Table 5.3: Dimensions of honeycomb structure

Length of each side (mm)	**Wall Thickness (mm)**	**Depth (mm)**
3.61	0.51	0.05

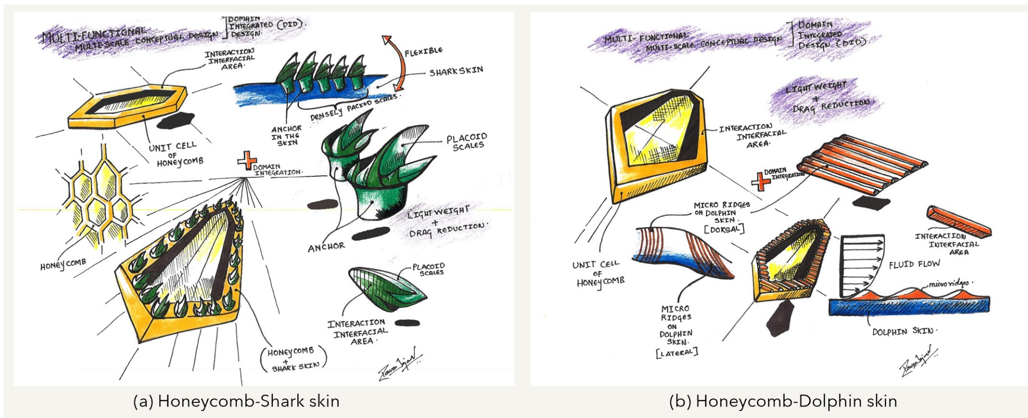
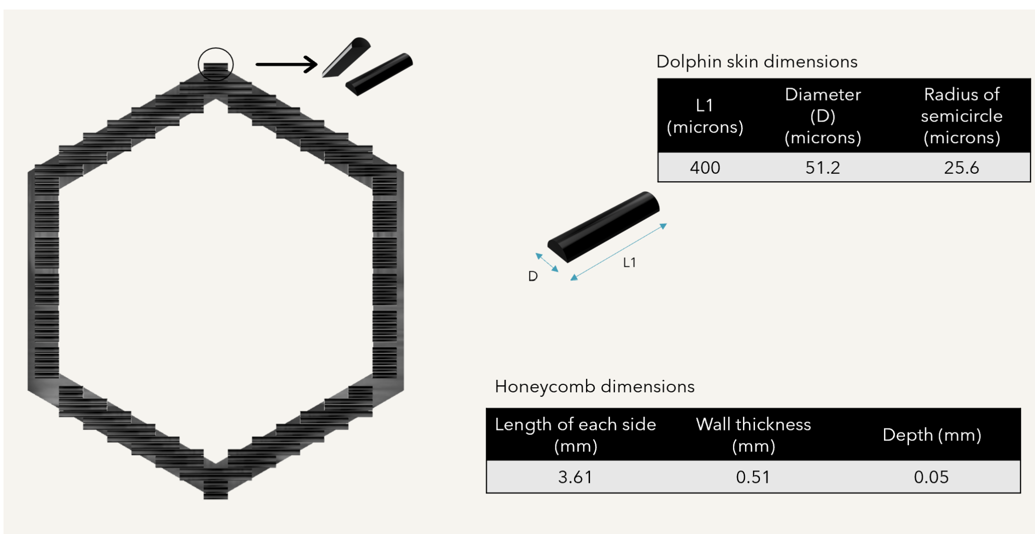


Figure 5.4: a) Conceptual sketch of the structure inspired by the combination of honeycomb and shark skin; b) Conceptual sketch of the structure inspired by the combination of honeycomb and dolphin skin.



Dolphin skin dimensions

L1 (microns)	Diameter (D) (microns)	Radius of semicircle (microns)
400	51.2	25.6

Honeycomb dimensions

Length of each side (mm)	Wall thickness (mm)	Depth (mm)
3.61	0.51	0.05

Figure 5.5: Design of the honeycomb-dolphin skin inspired lightweight and drag-reducing structure

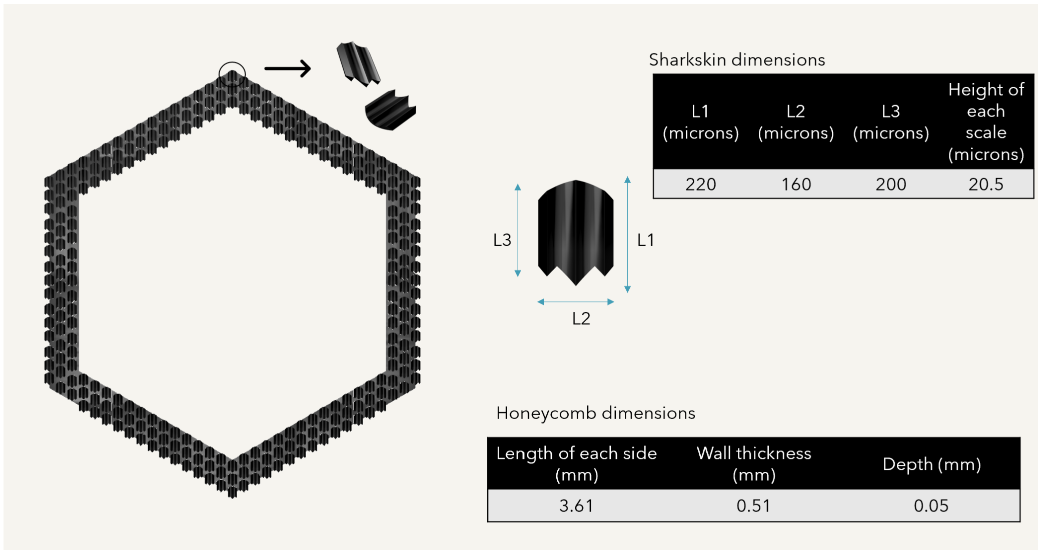


Figure 5.6: Design of the honeycomb-shark skin-inspired lightweight and drag-reducing structure

Table 5.4: Dimensions of Dolphin skin structure

L1 (microns)	**Diameter D (microns)**	**Radius of the semicircle (microns)**
400	51.2	25.6

Table 5.5: Dimensions of Sharkskin structure

L1 (microns)	**L2 (microns)**	**L3 (microns)**	**Height of the scales (microns)**
220	160	200	20.5

5.3.2 Experimental Setup

Simulations were conducted to assess drag-reducing performance by calculating drag force F_d and coefficient of drag C_d. Limited studies on skin compliance and pattern formation in dolphins for drag reduction were available [47]. However, attempts to analyze bio-inspired designs, specifically a flat plate with sharkskin and a flat plate with dolphin skin, resulted in software crashes. To address these issues, a comparative analysis was performed using only a single strip of sharkskin and dolphin skin, employing Double-precision, 3D flows, and the k-ω SST turbulent model in ANSYS R2022. Designs were generated using Rhinoceros v6. Importing microstructures into

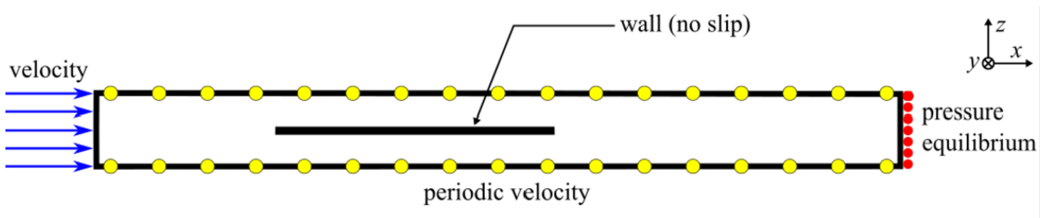


Figure 5.7: Simulation boundary conditions

ANSYS proved challenging, leading to the decision to scale up the designs by a factor of 10. This scaling approach aligns with previous studies that scaled shark denticles up to 12.4 times and surface ridges up to 16.2 times for physical experimentation [191]. In this study, scaling up the surface features addresses software limitations in capturing complex microstructural skin at its original microscales. The applied scaling ensures accurate digital encoding of mesh vertices locations, as the software cannot encode micrometers directly. The entire simulation domain, where the structure is placed, is scaled up homothetically by the same factor to maintain numerical results' invariance to the scaling factor. The simulation utilizes ANSYS R2022 CFD with computations performed in double precision, modeling turbulent flow in 3D through the k-ω SST model. Boundary conditions are imposed on the 3D parallelepiped simulation domain, as illustrated in the (z, x)-plane cross-section diagram in Figure 5.7. On the inlet surface, a Dirichlet condition is applied to the fluid velocity, defining a non-zero velocity in the x-component (while the other two components are fixed to zero). The outlet surface has a Neumann condition imposed on the pressure, setting the pressure gradient in the x-direction to zero for pressure equilibrium. The outer surface of the solid structure follows a wall condition (no-slip condition), where fluid velocity is zero in contact with the solid (also a Dirichlet condition). Periodic boundary conditions are set on the four other bounding planes of the computational domain, positioned sufficiently far from the obstacle (strip of

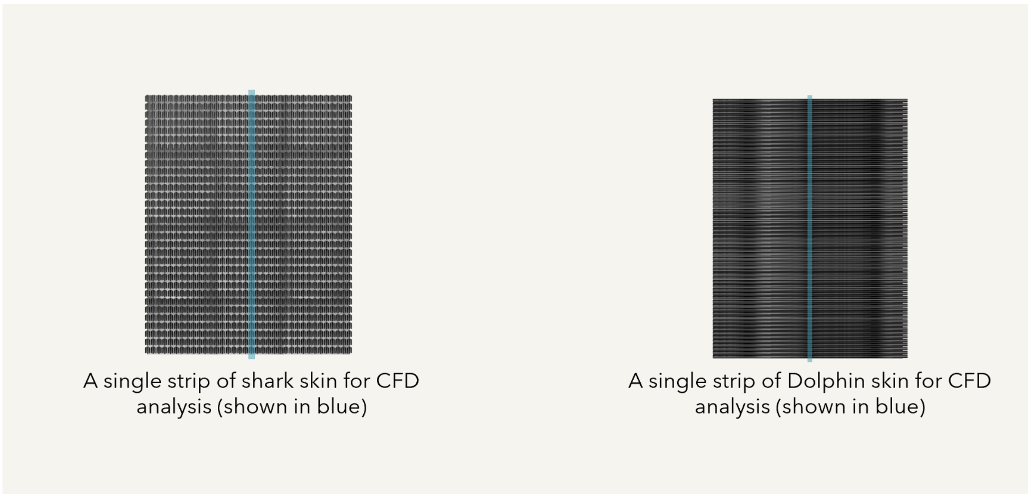


Figure 5.8: Extraction of single strips of shark and dolphin skin.

skin) to neglect their effect. This assumption is supported by the constant x-component of fluid velocity near the periodic boundaries in Figure 5.11, which remains constant for all components and settings in every simulation of this study. Drag force F_d and coefficient of drag C_d values are calculated

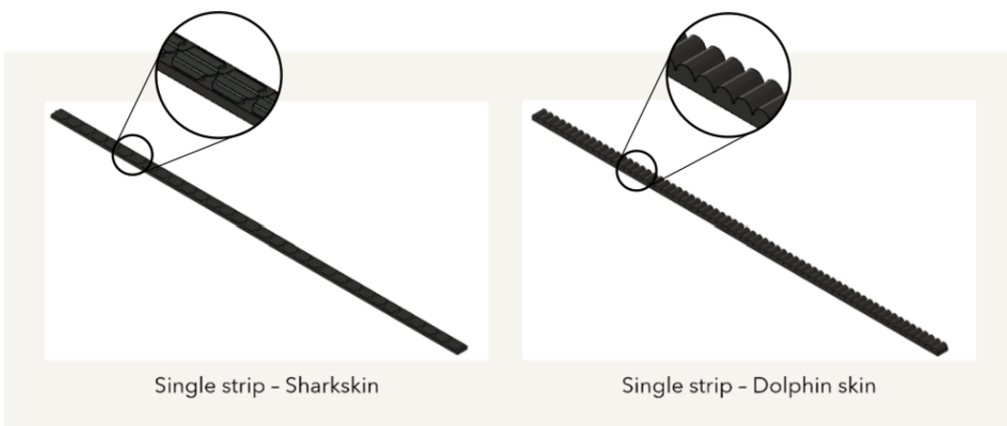


Figure 5.9: CAD images of the single strip shark and dolphins skin used for simulations.

at Reynolds numbers of 50,000 and 100,000. Previous studies indicate that small sharks swim at Reynolds number 29,000, while large sharks swim at Reynolds number 100,000 [193]. The velocity at the inlet is determined from the Reynolds number and the characteristic length [200, 201].

The L_{ch} is the characteristic length, Re is the Reynolds number, ρ = 1.225 kg/m3 is the density of water, and μ= 1.789 4 kg/(m s) is the dynamic viscosity. Finally, V is the velocity of the inlet.

A= $8.915x10^{-1}$ mm^2 is the cross-section reference area for the two strip structures for comparison purposes. This surface A corresponds to the rectangular area supporting the skin features. It is the rectangular cross-section area of the strip excluding the skin features. F_d is the drag force and V is the inlet velocity.

Figure 5.8 shows how the single strip was extracted from shark and dolphin skins highlighted in blue. The characteristic length for both strips is 72.20 mm. Figure 5.9 shows the CAD images of the single-strip shark and dolphin skins used for CFD simulations.

5.3.3 Simulation and Results

Table 5.6 shows the results of the CFD analysis performed on single strips of shark and dolphin skin at Reynolds number 50,000 and 100,000 respectively.

Table 5.6: Results of the Drag Force and Coefficient of drag (Cd) for Sharkskin and Dolphin skin for Reynolds number of 50,000 and 100,000 respectively

Biological Feature	**Reynolds Number**	**Velocity in m/sec**	**Coefficient of Drag c_d**	**Drag force in (N)**
Sharkskin	50000	0.69	9.1546E+02	9.5197E-04
Sharkskin	100000	1.38	3.0231E+03	3.1437E-03
Dolphin skin	50000	0.69	2.2276E+03	1.2164E-03
Dolphin skin	100000	1.38	7.5819E+03	4.1400E-03

Figure 5.10 illustrates the total interaction area of shark denticles and dolphin skin ridges, both scaled by a factor of 10, maintaining a constant interaction area ratio. A single riblet on shark skin has an interaction area of 0.39 mm^2, while a dolphin skin ridge has an interaction area of 0.71 mm^2. The findings reveal that shark skin, with its lower interaction area, more effectively reduces drag compared to dolphin skin. For Reynolds numbers of

50,000 and 100,000, the coefficient of drag C_d and drag force F_d for shark skin are significantly lower than those for dolphin skin. This confirms the initial hypothesis that, for a multifunctional application emphasizing anti-adsorption/absorption, repulsion, or reduction, features with a lower total interaction area should be selected. In Figure 5.11, the x-direction velocity plot demonstrates uniform fluid velocity throughout the domain, indicating the negligible impact of periodic boundary effects due to the domain's sufficient size.

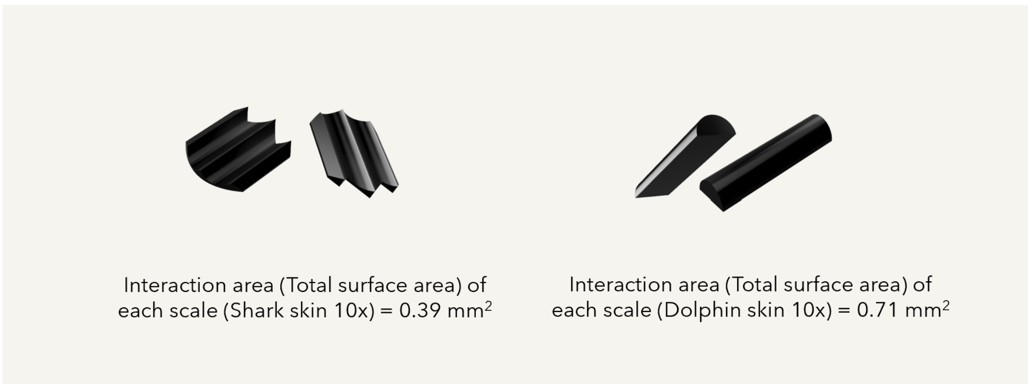


Figure 5.10: The total surface area of each scale for both shark and dolphin skin.

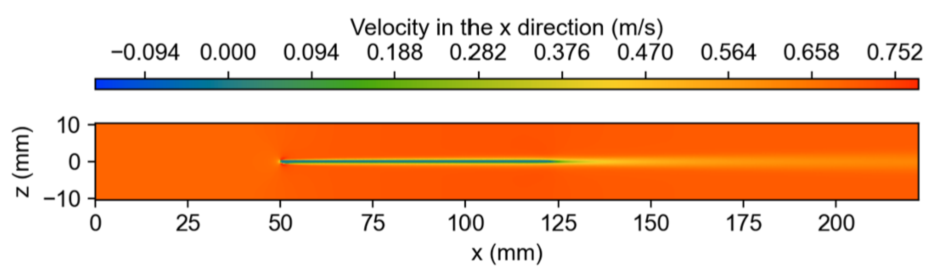


Figure 5.11: Plot of the flow velocity in x direction around the sharkskin strip with a Reynolds number of 50,000.

Designing microstructural features poses challenges, and their analysis is demanding. The conducted experiments don't replicate the undulatory motions of shark and dolphin skin, crucial for reducing drag. Early-stage product development doesn't necessitate detailed prototypes, and fixing parameters like material and dimensions is difficult. This simulation differs from previous studies, which physically printed structures and analyzed undulatory motion using a robotic arm in a tank-based setup. Analysis at Reynolds numbers 50,000 and 100,000 is limited, though swimming animals' Reynolds numbers are much higher. The chosen Reynolds numbers are based on printed structure length, not the actual animals. Meta-level design parameters serve as an initial screening, acting as a proof-of-concept for validating the total interaction area's importance in feature selection despite simulation challenges. Figure 5.12 depicts the probable application of the generated lightweight and drag-reducing structures in deep-sea explorations and deep-sea robotics.

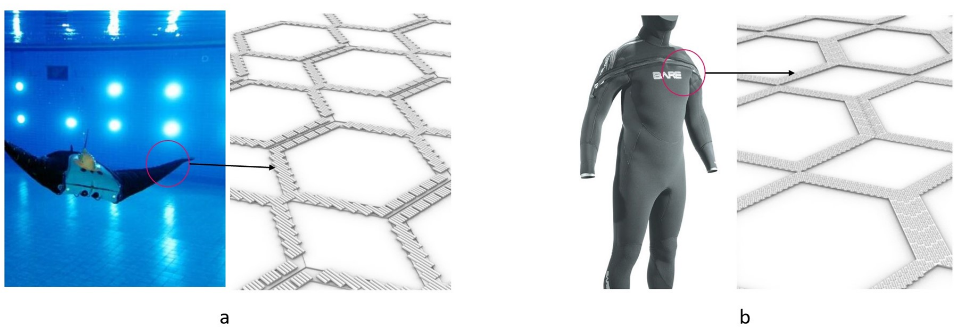


Figure 5.12: Application of the generated lightweight and drag-reducing structures in deep-sea robots and advanced swimsuits.

5.4 Estimation of meta-level design parameters between biological features of different geometrical significance and scale but with a similar functionality

In addition to the meta-level design parameters to select the features exhibiting similar functions with the same geometrical relevance and scale, additional quantitative parameters were established through an experimental study on the impact resistance function exhibited by two biological features namely, Balanus (Barnacles) inspired conical structure and woodpecker's beak inspired porous cellular structure. A new multifunctional helmet design is conceptualized following the DID method [41].

The idea involves merging biological characteristics categorized by their specific geometric attributes to create versatile designs. For instance, the multifunctional helmet is formed by blending the streamlined form of a penguin's body to reduce drag on the outer surface [106], a structure inspired by a luffa sponge for efficient water (sweat) absorption [115], and designs drawn from a woodpecker's beak [189] and Balanus shell [32] for the helmet's interior lining. section 5.4 provides a breakdown of these biological features, which are categorized and combined to craft a multifaceted, bio-inspired helmet design.

Table 5.7: Biological features, their functions, and their corresponding domains

Biological Feature	Function	Domain
Body shape (Penguin)	Drag reduction	Shapes
Sponge (Luffa)	Water absorption (sweat)	Cellular Structures
Beak (Woodpecker)	Impact resistance	Cellular Structures
Outer shape (Balanus)	Impact resistance	Shapes

Figure 5.13 illustrates the conceptual layout of the multifaceted bio-inspired helmet design, addressing various functions by integrating diverse

biological features with distinct geometric designs and functionalities. Mov-

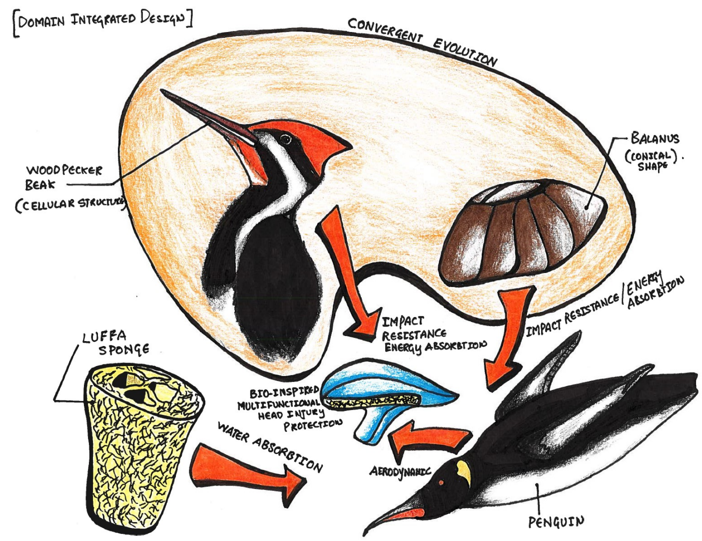


Figure 5.13: Conceptual sketch of the Multifunctional Bio-inspired helmet design inspired by multiple biological features such as a penguin's body, luffa sponge, woodpecker's beak, and Balanus shape

ing to Figure 5.14, it presents the proposed outer shell design of the helmet, drawing inspiration from the streamlined shape of a penguin's body to effectively minimize drag. Additionally, the inclusion of luffa sponge-inspired cellular structures along the helmet's sides aims to efficiently absorb water, reducing sweat accumulation during bicycle rides. In Figure 5.15, the conceptual depiction showcases the helmet liners designed for optimal impact resistance, inspired by both the woodpecker's beak structure and the Balanus-inspired design. Notably, the woodpecker's beak structure exhibits a gradient porosity within its cellular makeup, with the outer and bottom layers at 30 percent porosity, while the middle layer stands at 65 percent porosity [189]. These bio-inspired structures are anticipated to conform to the skull's shape.

5.4.1 Experimental Setup

The existing body of literature documents a series of tests conducted to verify the efficacy of various helmet designs. For instance, bicycle helmets underwent oblique impact testing involving a free-falling head form colliding with

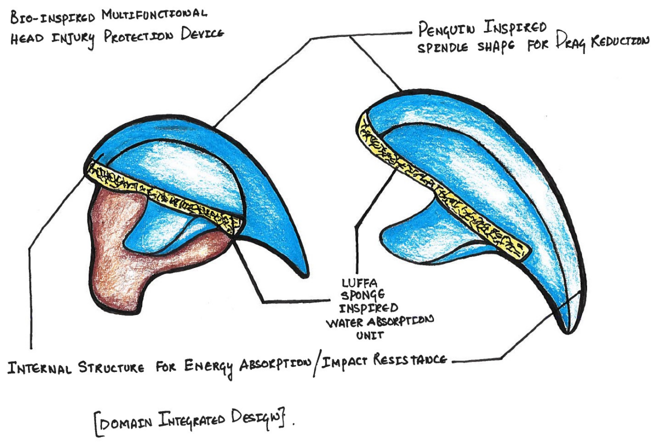


Figure 5.14: Conceptual sketch of the Luffa sponge-inspired structure on the lateral edges of the helmet design used for effective sweat absorption.

a horizontally moving structure composed of two aluminum plates, with impact measurement done using tri-axial quartz force cells [202]. Assessments of energy absorption in shin-guard structures during low-velocity impacts were carried out using a twin-wire guided vertical impactor [203]. The BMW Group conducted tensile tests on metal cellular structures [204]. A recent study utilized LS-DYNA to simulate a polycarbonate impactor model, comparing the effectiveness of pomelo fruit, woodpecker beak, and shell designs. Results indicated that the Pomelo structure exhibited lesser deformation compared to woodpecker and shell designs [205]. Figure 5.16 shows the experimental setup used for assessing the impact force and displacement. The experiments were conducted at the Biokinetics and Associated LTD, Ottawa. However, in alignment with ASTM F1952 standards [206], the current designs opted to undergo testing involving an incremental drop height of up to 1.6 meters. An incremental height was chosen to capture the effective energy absorption observed in the structures. A flat energy-absorbing material is positioned between these two things, and the flat impactor is dropped onto the foam sample at the required speed. The drop mass is 5kg. Figure 5.4.1 presents the experimental specimens, dimensions, and impact velocities under which the impact resistance of structures was recorded.

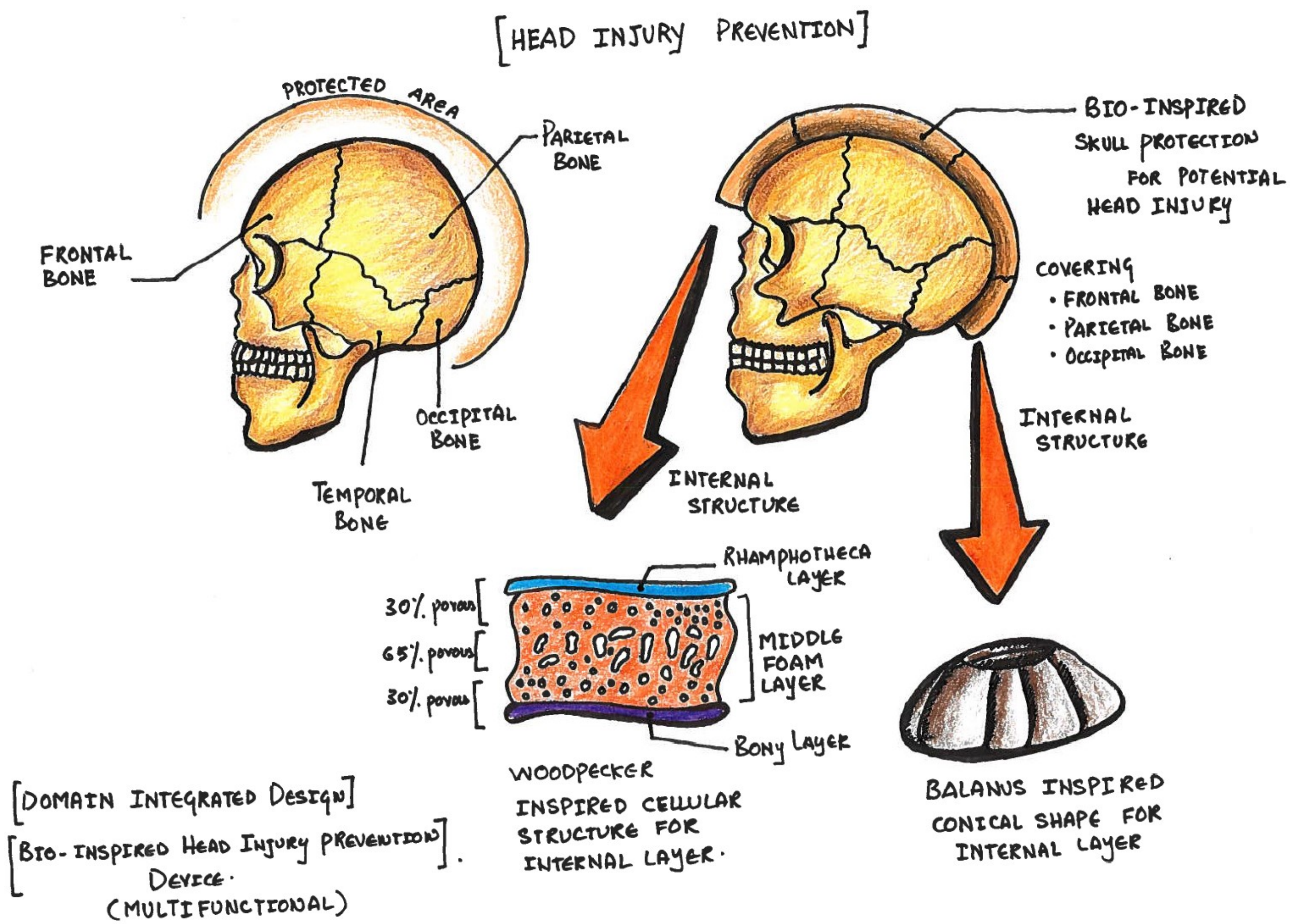


Figure 5.15: Conceptual sketch showing conformal helmet liners inspired by the woodpecker's beak structure and the Balanus-inspired structure.

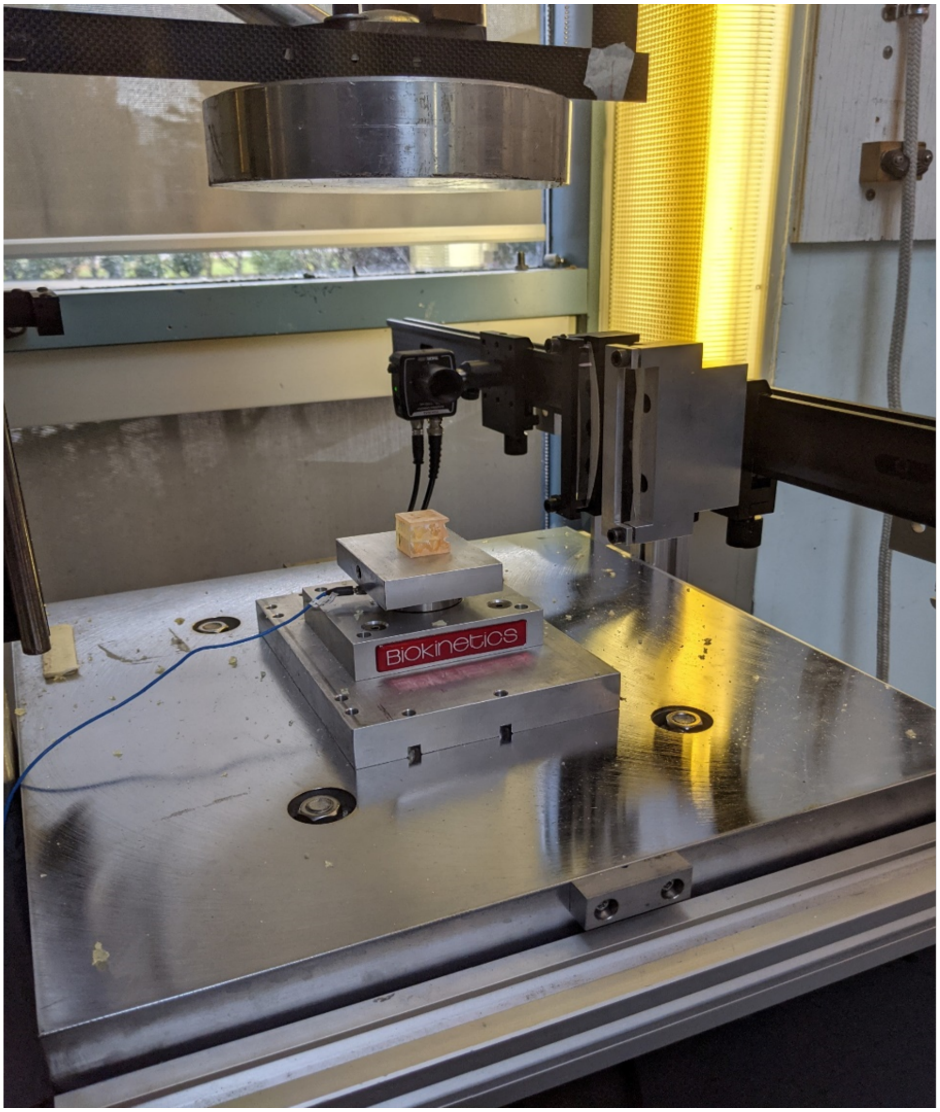


Figure 5.16: The testing equipment used for the impact force and displacement measurement (Courtesy: Biokinetics and Associates LTD, Ottawa)

Table 5.8: Experimental setup specimens, dimensions, and impact velocity

Test	Samples	Sample dimension (mm)	Impact velocity (m/sec)
Test 1	Woodpecker and Balanus	50x50x50x23.5	3.96
Test 2	Woodpecker and Balanus	24x24x23.5	3.98
Test 3	Woodpecker and Balanus	24x24x23.5	4.84
Test 4	Woodpecker and Balanus	24x24x23.5	5.61
Test 5	Woodpecker (slender) and Balanus (slender)	100x5x23.5	5.59

5.4.2 Experimental Results

The following graphs illustrate the peak force recorded for both the woodpecker beak and Balanus-inspired structures upon impact. The woodpecker sample is represented by the blue line, while the Balanus sample is denoted by the orange line. The graphical representation demonstrates the superior performance of the Balanus structure over the woodpecker beak structure in effectively absorbing the peak force generated during impact. Experimental studies on the performance of sandwich panels to resist impact reported that materials with structural hierarchy have a better stiffness-to-weight ratio than their single-scale counterparts. For example, Second-order corrugated core structures showed a 10-fold improvement in performance as compared to first-order corrugated structures. Similarly, bi-directional corrugated topology showed superior performance than one-directional corrugated core [207]. The localized corrugations on the structures postpone the elastic buckling of the main corrugated core. [207]. Figure 5.17 and Figure 5.18 depicts the slender CAD models of woodpecker's beak-inspired structures and the Balanus-inspired conical frustum core structures. Figure 5.19 and Figure 5.17 depicts the 3D printed structures balanus-inspired and wood-

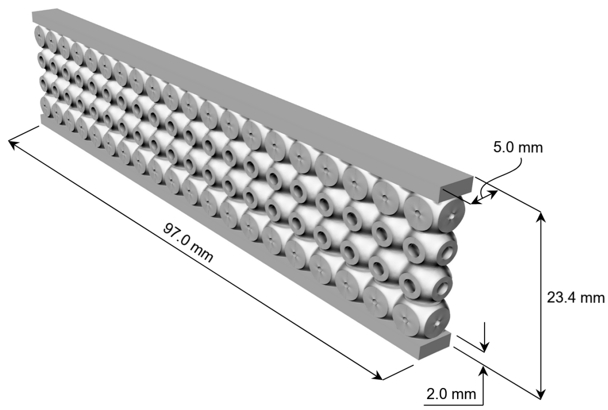


Figure 5.17: The CAD model of the slender woodpecker's beak-inspired cellular structure with porosity gradients.

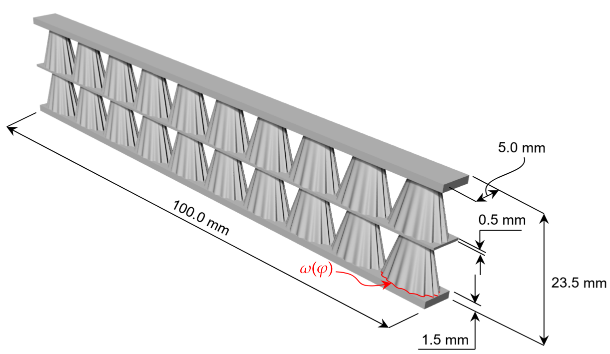


Figure 5.18: The CAD model of the slender Balanus-inspired conical structure with corrugations on each unit cell resembling a second-order corrugated structure.

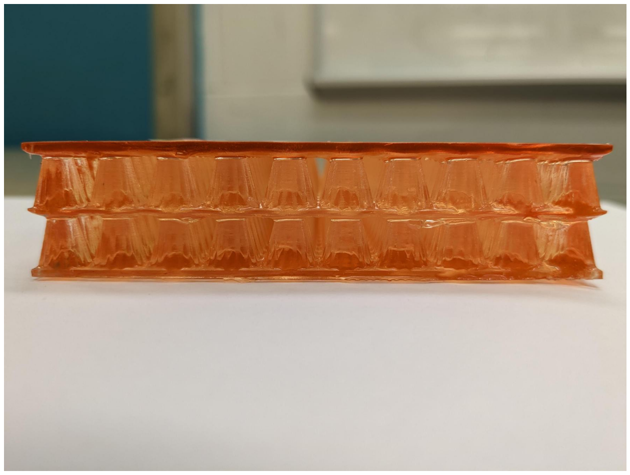


Figure 5.19: 3D printed Balanus-inspired conical corrugated core structure used for impact testing. The material used for 3D printing is from Formlabs (medical grade)

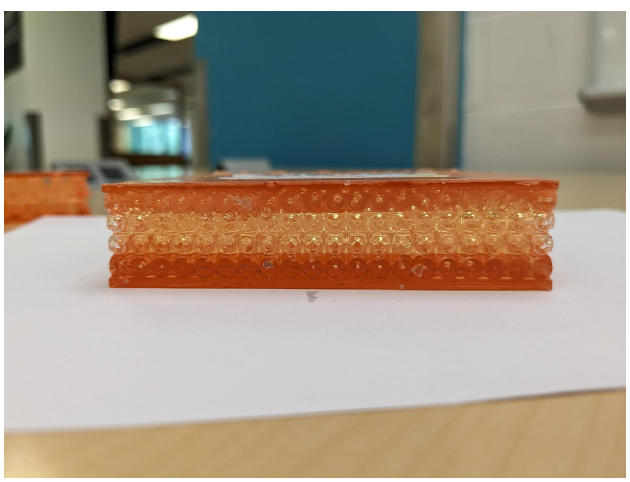


Figure 5.20: 3D printed woodpecker-beak inspired structure used for impact testing. The material used for 3D printing is from Formlabs (medical grade)

peckers beak-inspired respectively that are used for physical testing. The material used to 3D print the structures is Formlab's Biomed (Amber).The details of the material can be found at [208] Recommendations were given for improved performance of the sandwich panels such as reduction in the height-to-thickness of the corrugated core, thickness of the core-to-thickness of face sheets, and length of unit cell-to-the height of corrugation. In another research study, it was reported that load deformation is significantly influenced by the semi-apical angle of a conical frustum. As the semi-apical decreases, the conical frustum becomes more steep and undergoes more deformation thus, absorbing more energy [209]. However, the parameter in this case would be to stiffness-to-weight ratio. The higher the stiffness-to-weight ratio better the performance.

Figure 5.21 depicts the peak force observed in the woodpecker beak-inspired structure and the Balanus structures at an impact velocity of 3.96 m/sec. The Balanus-inspired structure showed a better absorption of peak force. Figure 5.22depicts the peak force observed in the woodpecker beak-

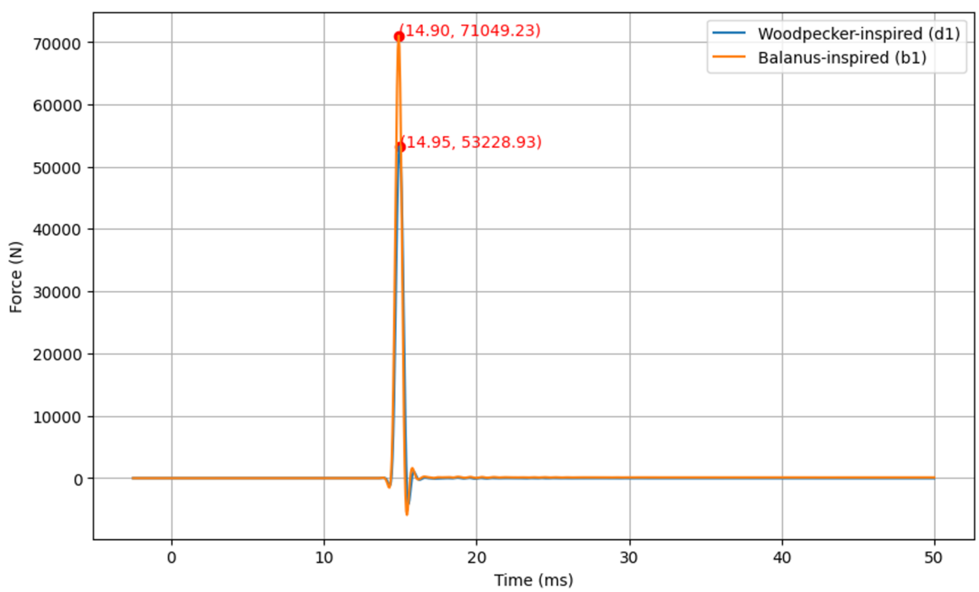


Figure 5.21: Peak Force observed in Woodpecker Vs Balanus at an impact velocity of 3.96 m/sec

inspired structure and the Balanus structures at an impact velocity of 3.98 m/sec. The Balanus-inspired structure showed a better absorption of peak force. Figure 5.23depicts the peak force observed in the woodpecker beak-

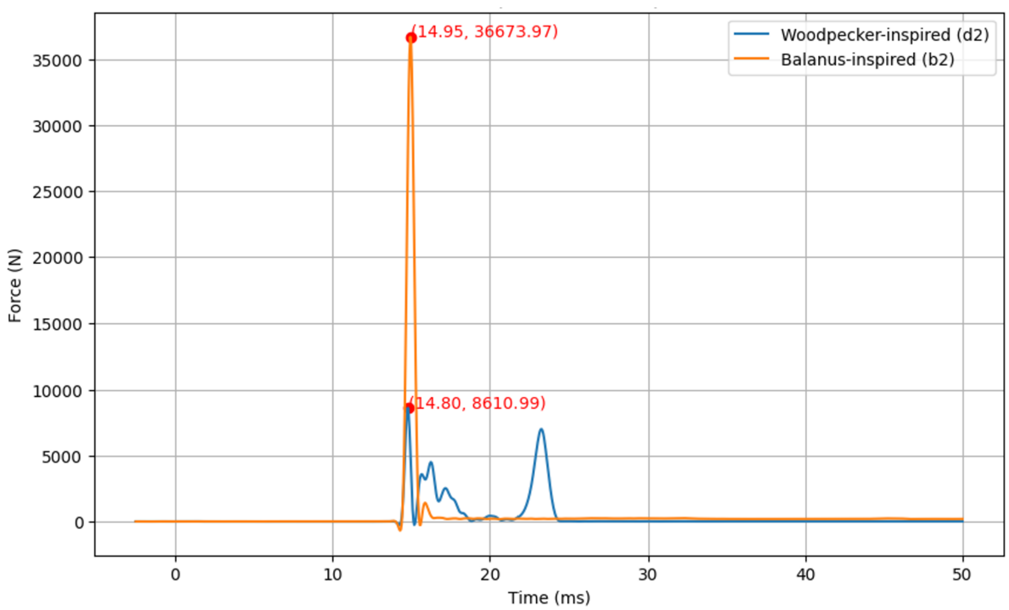


Figure 5.22: Peak Force observed in Woodpecker Vs Balanus at an impact velocity of 3.98 m/sec

inspired structure and the Balanus structures at an impact velocity of 4.84 m/sec. Similar to the above results, the Balanus-inspired structure showed a better absorption of peak force. Figure 5.24depicts the peak force observed in the woodpecker beak-inspired structure and the Balanus structures at an impact velocity of 5.61 m/sec. This is a recommended velocity for impact testing for bicycle helmets according to the ASTM standards. The Balanus-inspired structure showed a better absorption of peak force. Figure 5.25 depicts the peak force observed in the slender columns of the woodpecker beak-inspired structure and the Balanus structures at an impact velocity of 5.59 m/sec. The structures used in this study are slender columns and were tested for a precise understanding of the impact performance observed in both structures. However, the Balanus-inspired structure showed a slightly better absorption of peak force. From the results, it is evident that the Balanus structures have a hierarchical corrugated core structure, making it a second-order corrugated structure. The peak force absorption is better in the case of the Balanus-inspired structure as compared to the woodpecker

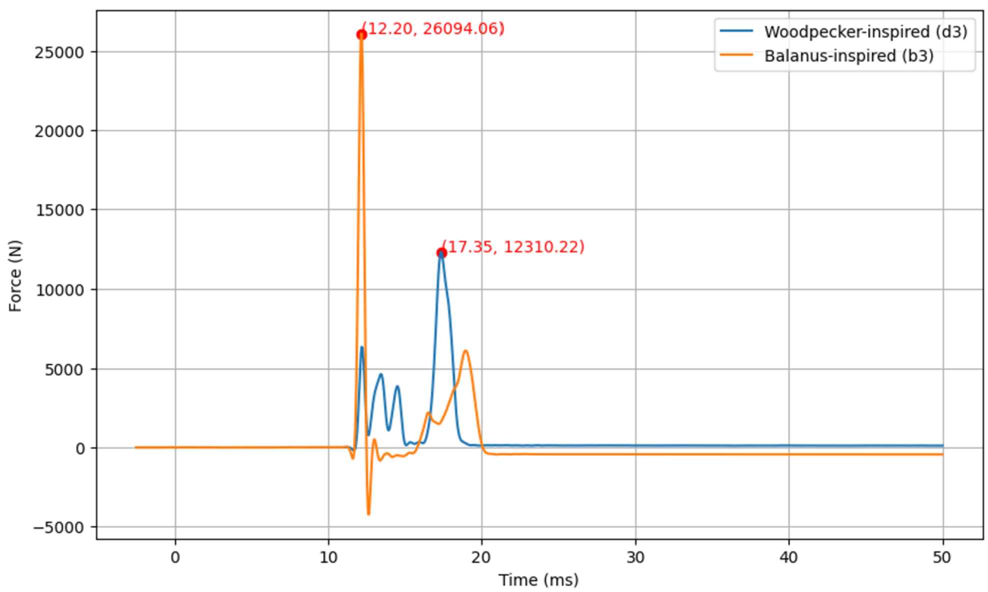


Figure 5.23: Peak Force observed in Woodpecker Vs Balanus at an impact velocity of 4.84 m/sec.

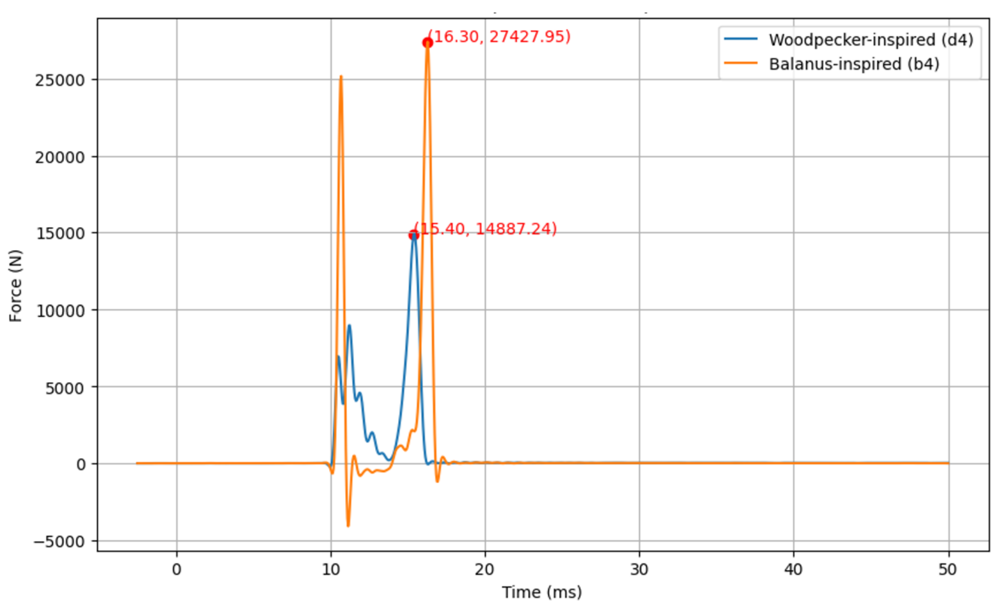


Figure 5.24: Peak Force observed in Woodpecker Vs Balanus at an impact velocity of 5.61 m/sec

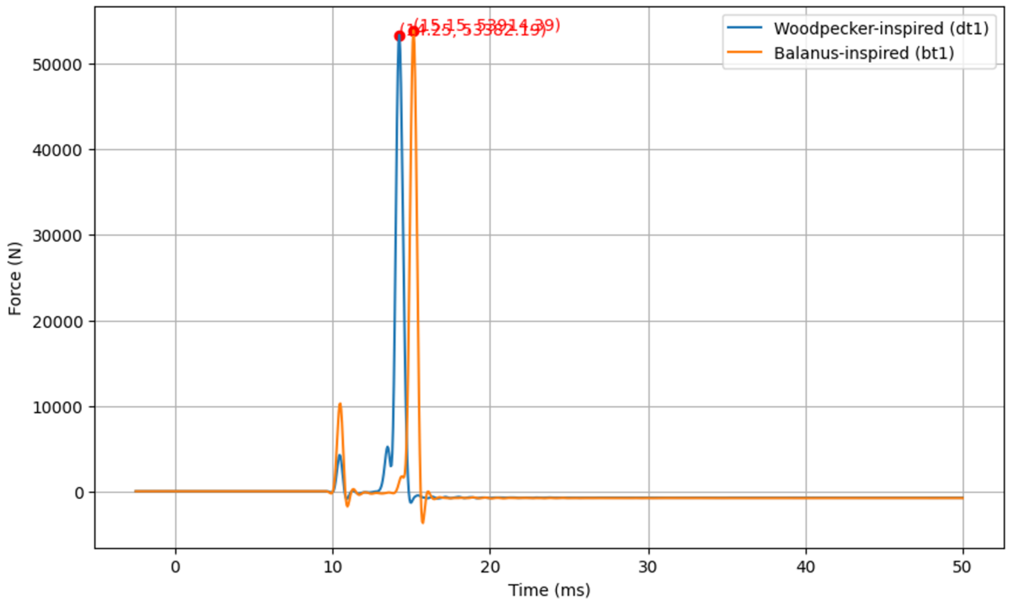


Figure 5.25: Peak Force observed in Woodpecker Vs Balanus at an impact velocity of 5.59 m/sec

beak structure. The deformation in the case of woodpecker beak is more as compared to that of Balanus-structure. This explains that the woodpecker's beak structure absorbs more energy but is less resistant to impact. The structures employed for protection against potential injuries must be efficient in absorbing energy and at the same time resistant to failure.

Future work

The future scope of this work is to perform computer simulations on unit cells to verify the effectiveness of hierarchical structures in impact resistance as compared to cellular structures. This provides more precise information in establishing a parameter for the selection of relevant biological features with a different geometrical relevance and scale but exhibits the same functionality.

5.5 Summary

This study establishes quantitative meta-level design parameters for selecting biological features with similar geometric relevance and functionality. Convergent evolution in nature leads to distinct organisms developing traits to meet similar needs. To aid inspiration selection, precise criteria, such as total interaction area derived from cellular and crystal formation principles, are proposed. A case study on shark and dolphin skin shows that low total interaction area in sharkskin reduces drag compared to dolphin skin. Full-scale simulations and physical testing are required in the detailed design phase. Additionally, the physical experiments conducted to establish parameters for the features that exhibit the same functionality but have different geometric relevance and scale revealed that the stiffness-to-weight ratio plays a prominent role in absorbing the energy and resistance to impact. However, further verification is required to precisely define the parameter.

In the process of BID (Biologically Inspired Design), it becomes crucial to draw inspiration from various biological sources to meet diverse design needs and overcome challenges. The suggested meta-level design parameters have the potential to be integrated into various continually evolving multi-functional bio-inspired design approaches. Their quantitative criteria significantly aid in choosing biological features in the early embodiment design stages.

Existing literature tends to take a more comprehensive approach to selecting biological analogies, mainly focusing on design requirements and applying them during the initial stages of conceptual development. Unlike the qualitative criteria commonly used in current design methods for conceptual design, the newly proposed parameters offer quantitative criteria. This enables the precise selection of crucial biological features in the early phases of design embodiment.

6

The Expandable Domain Integrated Design (xDID) Model

This chapter details the complete process model of a bio-inspired concept generation system termed the Expandable Domain Integrated Design (xDID) Model. The xDID model incorporates the BIKAS knowledge database, DID method and the meta-level design parameters in generating unique and novel multifunctional conceptual designs. The contents of this chapter are reported in Designs Journal [13]

6.1 The xDID Model

The xDID model streamlines the process of amalgamating diverse biological features by categorizing approximately 50 biological features, abstracted from case studies, into specific geometric designations referred to as domains. These domains are then correlated with the corresponding tissues of origin. The xDID model effectively integrates the previously introduced classification and mapping of biological features with the representation of embodiment function, creating a systematic approach. This integration enables the combination of biological features from different domains, leading to the generation of multifunctional design concepts. As shown in Figure 6.1, the initial step involves the acquisition and representation of biological features at their embodiment level to ease the existing complex system-level abstraction of biological features. The next step involves classifying biological features based on their characteristic traits into their respective geometric designations, known as domains. These domains represent various biological features performing distinct embodiment functions linked to their respective tissues through a shared geometric designation. Shapes and cross-sections are sub-domains within surface and cellular structures, exhibiting biological feature characteristics associated with their respective domains. This classification of the biological features enables the rapid and appropriate selection of biological features based on their structure, configuration, and function. The next step is mapping the classified biological features to the tissues from which they originate. This mapping bolsters comprehension and utilization of the feature's structural makeup and material composition. This process kickstarts and ensures the exploration of suitable materials for new designs that align with the properties found in biological substances. Doing so paves the way for a more informed selection of materials that mimic or complement the exceptional traits observed in natural biological structures. The final step is to utilize the meta-level design parameters to select appropriate biological features from those that exhibit the same function and have a similar geometrical relevance and scale.

Figure 6.2 portrays the xDID model concept generation flow chart. Utilizing the Figure 6.2, various biological features demonstrating diverse functions and categorized into specific geometric designations are retrieved from the BIAKS (knowledge database) based on the design requirements. The subsequent stage involves applying meta-level design parameters to identify the most suitable biological feature. This selection process operates iteratively, involving a continuous cycle between retrieval and application of design parameters. Once the selection is made, the integration of biological features occurs, leading to the creation of the multifunctional bio-inspired concept. Finally, the concept undergoes validation through simulation and comparative analysis with existing conventional designs that address similar functions.

The subsequent sections provide case studies developed to validate the effectiveness of the xDID model.

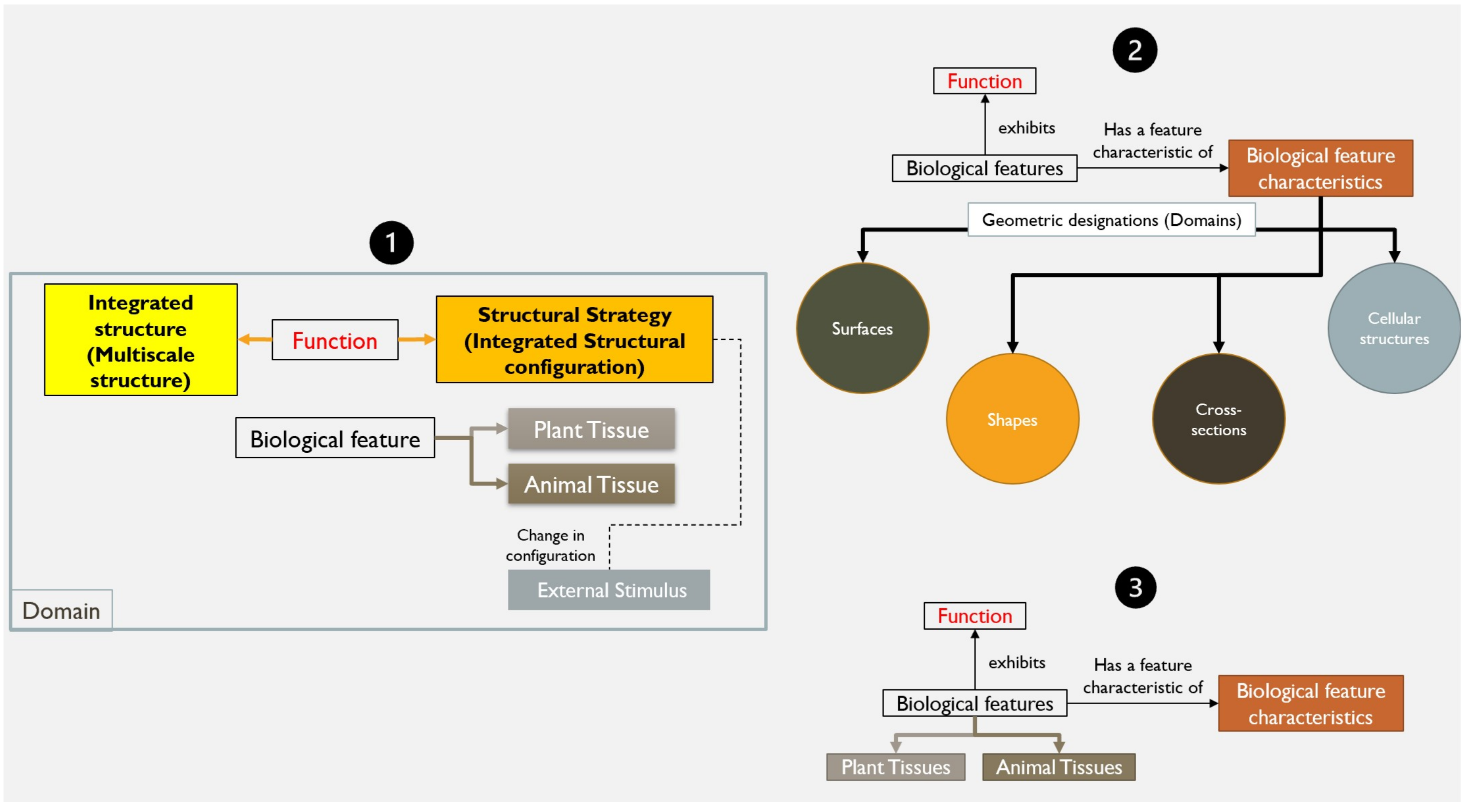


Figure 6.1: xDID Model detailing the entire design process starting from 1) Acquisition and representation of biological features, 2) classification of biological features into domains, and 3) mapping of the features to their tissues.

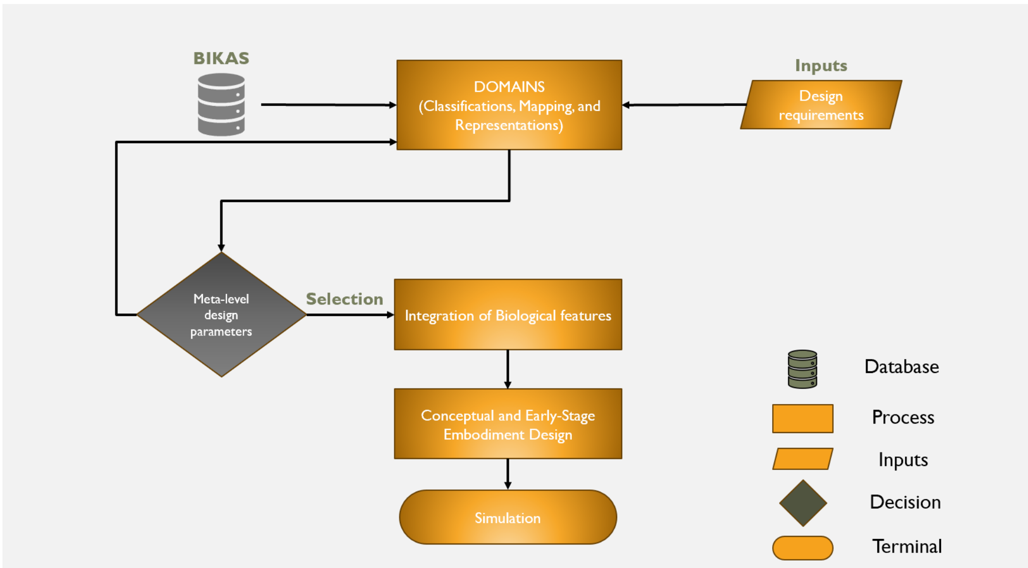


Figure 6.2: Multifunctional Bio-inspired Design Concept generation flowchart

6.2 Summary

xDID extends the DID method to accommodate the increasingly intricate categorization of complex biological features based on characteristics that surpass the presently defined Domains. Additionally, xDID functions as a model that incorporates the classification, mapping, and application of proposed meta-level design parameters in selecting pertinent biological analogies for combination. This model enables the utilization of various components within the idea generation system.

- **BIKAS**: Facilitating understanding regarding the function performed by the biological feature
- **DID**: Enabling the selection and combination of features based on their function and geometrical relevance.
- **Meta-level design parameters**: Supporting the selection of pertinent biological analogies.

Part V

Validation

7

Generation of novel multifunctional bio-inspired early stage embodiment designs using the xDID model

The validation of a systematic bio-inspired design is verified through two approaches. As shown in figure 7.1 a), the first one is to search if the method reproduces an existing biomimetic product through a literature survey. The second is to see if there are any closely related development versions of concepts developed using the method in the literature [69]. However, if the generated concepts are novel biomimetic concepts, the validation is through a literature review to quantify if the concept variants are realistic or just science fiction [69]. Figure 7.1 b) defines the approach for validation of the MBID idea generation system. The MBID system aims at generating novel biomimetic designs. The verification in this research aims to determine whether the method can generate novel and unique multifunctional conceptual designs. Validation of these generated novel and unique multifunctional concepts was conducted through simulation-based comparisons

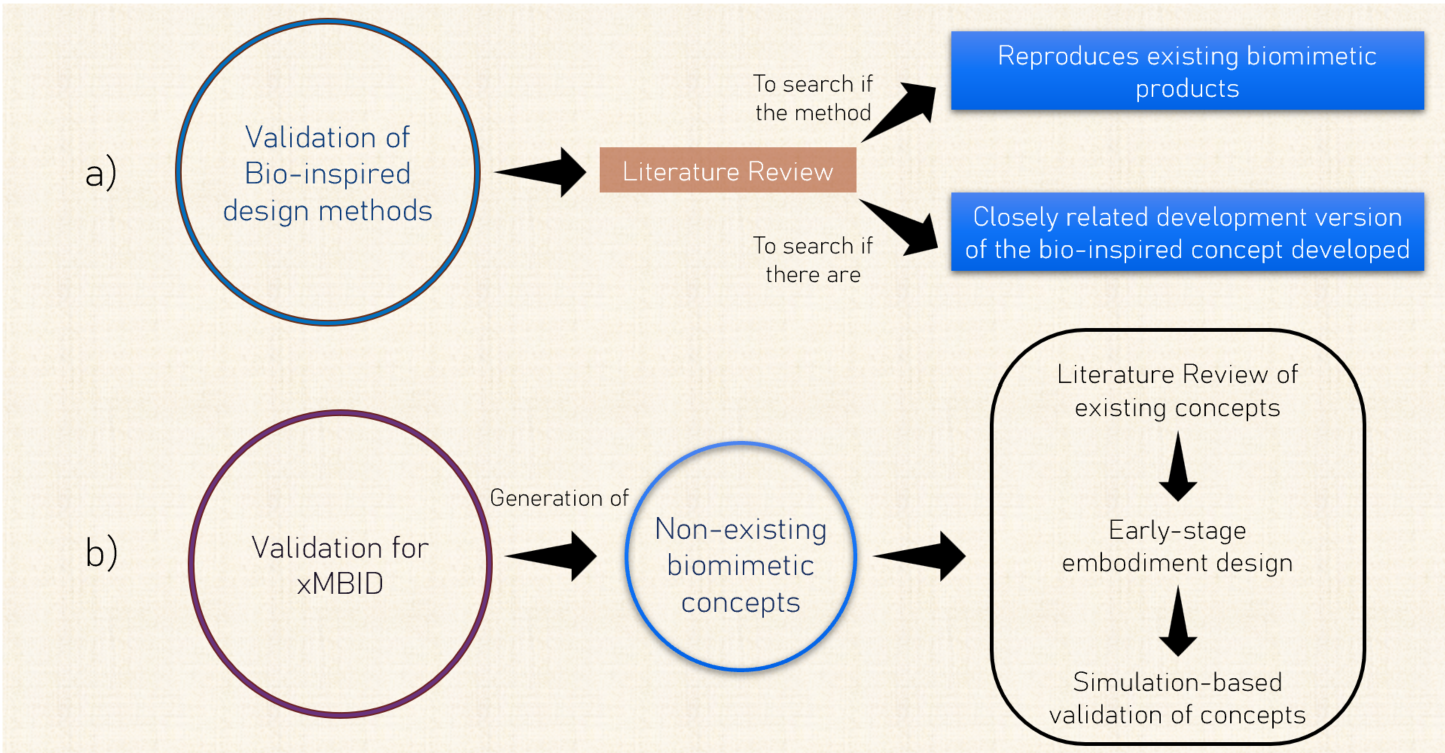


Figure 7.1: A schematic representation of the validation of MBID vs Systematic bio-inspired design methods. a) validation through effective reproduction of existing biomimetic products or by finding closely related development versions of concepts developed through literature search. b) Validation by generation of novel bio-inspired designs and comparison with existing designs by simulation-based verification.

with existing designs. The examples of Bio-Inspired Design (BID) were collected from various research articles, detailing the functions performed by features. In this research, the gathered BID examples were categorized according to their function, feature, feature characteristic, integrated structure, and structural strategy. Additionally, these examples were mapped to their respective geometric designations, termed Domains. The novel multifunctional bio-inspired designs, as demonstrated in the case studies, were generated by utilizing structures classified into their respective domains. The next phase of the research will involve utilizing structures classified into micro-domains. This phase will see the advancement of the classification of biological features into micro-domains evolving concurrently with the expansion of the BIKAS knowledge database. The novel multifunctional bio-inspired designs, as demonstrated in the case studies, were generated by utilizing structures classified into their respective domains. The next phase of the research will involve utilizing structures classified into micro-domains. This phase will see the advancement of the classification of biological features into micro-domains evolving concurrently with the expansion of the BIKAS knowledge database. The following case studies present each bio-inspired multifunctional design concept developed using the MBID approach. The contents of the case-study 1 have been reported in [111], case-study 2 in [189], and case-study 3 in [210].

7.1 Case-study 1:Bio-inspired multifunctional painless sutures

In this design research, a composite approach utilizing the functionalities of two distinct organisms was employed to achieve a versatile bio-inspired design for suture pins. The conceptualization of the suture pin drew inspiration from the distinctive features of both a kingfisher's beak and a porcupine quill. The fundamental structure of the pin is based on the unique rotational parabolic cross-section design observed in a kingfisher's beak, facilitating seamless prey capture during the transition from low-density air to high-density water without creating a splash [18]. Expanding upon this framework, the integration of porcupine quills, with their micro barbs, enhances the pin's ability to swiftly penetrate the skin and resist easy removal. Consequently, the amalgamation of these features results in a novel bio-inspired suture pin design characterized by low puncture force, prolonged retention in the skin until complete wound healing, and resilience to external disturbances.

A thorough understanding of needle-tissue interaction, particularly puncture force and tissue deformation during operation, is essential to comprehend the prerequisites of suture needles' design. The following is a comprehensive overview of diverse experiments conducted on needle-tissue interactions, encompassing varied needle shapes, insertion velocities, and insertion angles. Bao X et al [211], Chebolu A et al [212], and Li.R-D et al [213] identified several key factors that exert influence on puncture force and tissue deformation.

- Stiffness: The puncture force depends upon the stiffness of the needles.
- Influence of velocity: The initial puncture force diminishes significantly with an increase in insertion velocity.
- Influence of angle: The puncture force is at its minimum when the angle reaches 90 degrees, indicating that the needle punctures vertically into the tissue surface.

In an experimental study focused on assessing needle deformation, a trocar needle was introduced into five phantom specimens at a consistent velocity of 2.5 mm/s. The study revealed that the reaction force on the needle during puncture was approximately 0.90 N, and the volume of tissue deformation peaked at the puncture point [214]. These experiments underscore the dependence of puncturing force on stiffness, insertion velocity, insertion angle, and needle tip shape. The simulation and validation for the bio-inspired suture pin are conducted based on these influential factors. This research introduces a conceptual design for a new surgical staple leg, combining features from a kingfisher's beak and porcupine quills to achieve multifunctionality. The kingfisher's beak is employed to mitigate patient discomfort by reducing insertion force, while the porcupine quills prevent the suture pin from being easily removed and protect it from external disturbances. Throughout this research, the newly designed surgical staple leg/needle is referred to as a bio-inspired suture pin-leg/needle. Subsequent sections elaborate on the design and simulations in detail. The research validates the bio-inspired suture pin-leg/needle design based on two criteria: tissue deformation at the puncturing moment and needle deformation at the puncturing moment.

7.1.1 Design Process

The design process entails classifying, mapping, and representing biological features according to their respective geometric designations known as do-

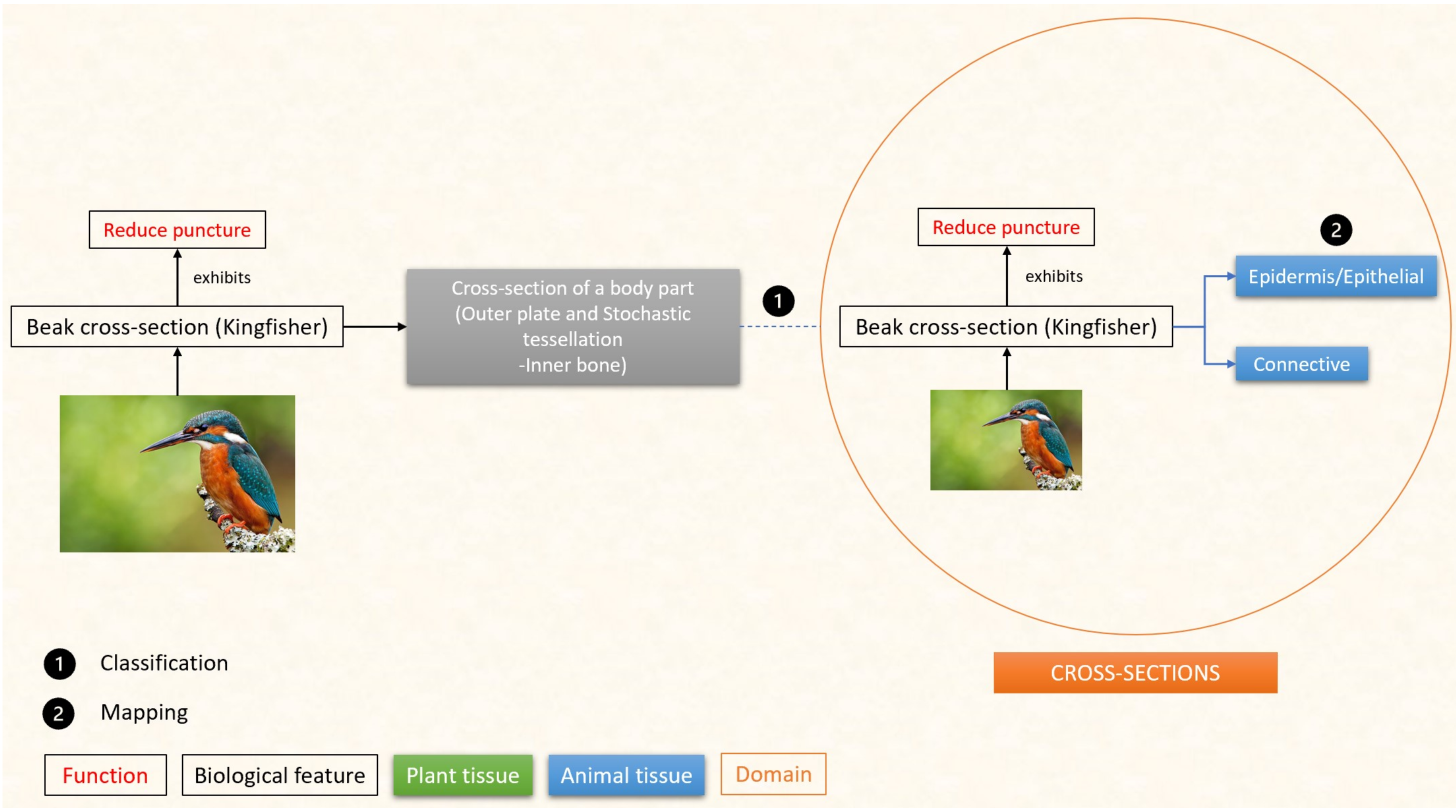


Figure 7.2: Classification and mapping of the kingfisher beak (cross-section) to its respective geometric designation (Domain) and the respective tissue from which it originated.

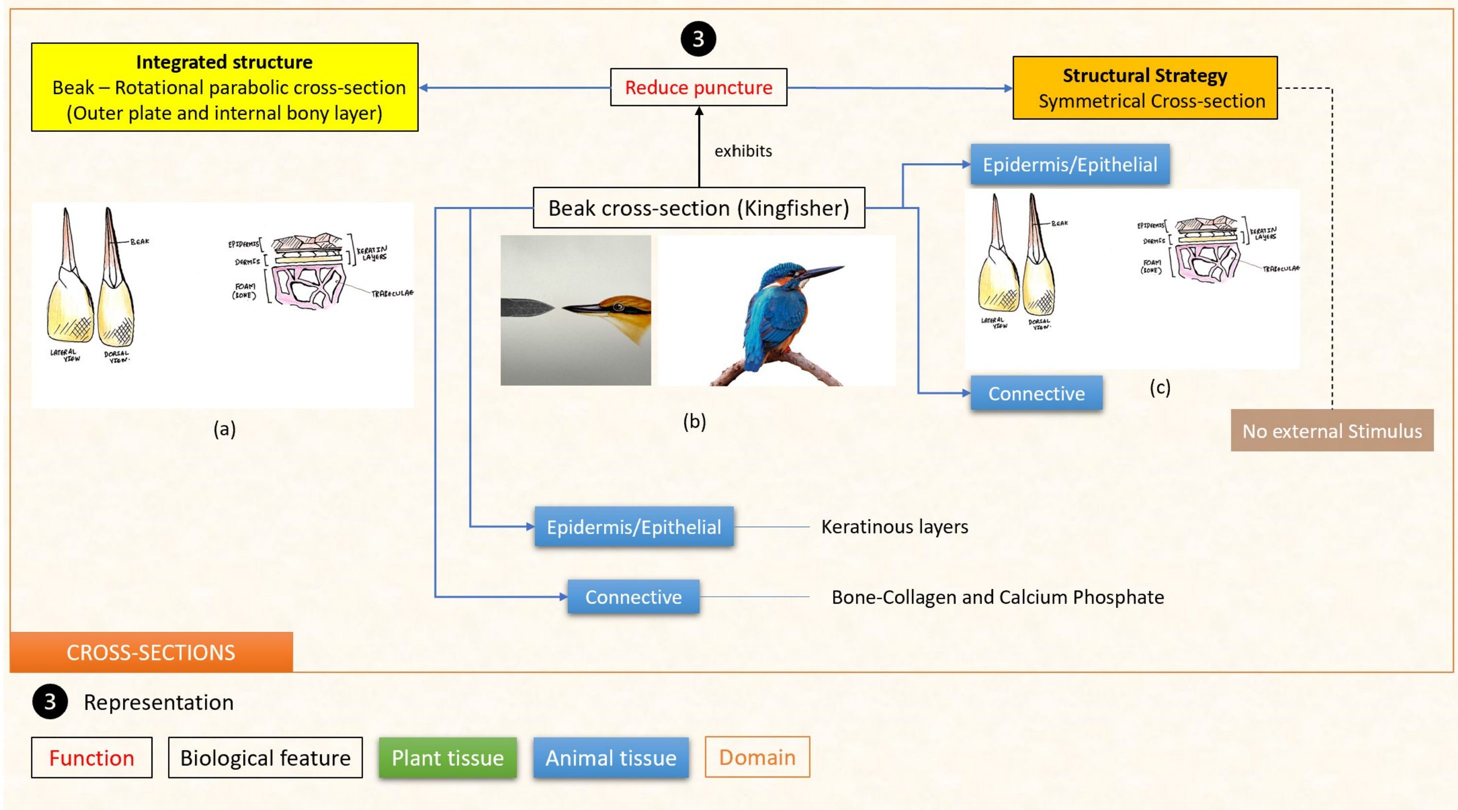


Figure 7.3: Representation of the function as a combination of structure and structural strategy. Images inspiration a) [17], b) [18], c [19].

mains. Additionally, it involves mapping these features to the tissues from which they originate and representing the function exhibited by the feature as a combination of integrated structure and structural strategy. One could formulate a hypothesis suggesting that the rotational parabolic cross-section observed in a kingfisher's beak, which is naturally employed at high velocities for penetrating from low-density to high-density regions to capture prey, would be highly fitting for the structure of a suture pin-leg. In conjunction with the rotational parabolic cross-section, triangular micro-projections inspired by porcupine quills, specifically the barbs, were incorporated to deter the removal of the suture.

1. **Classification**:In Figure 7.2 the classification of the kingfisher beak's cross-section is depicted, showcasing biological features characteristic of a cross-section of a body part. This cross-section is composed through the amalgamation of hard outer plates and stochastic tessellation (inner bone). Refer to Figure 7.3 for a visual representation of the mapping of the kingfisher's beak to its corresponding biological tissue, wherein the kingfisher's beak cross-section is designated as the domain of the cross-section. Likewise, as illustrated in Figure 7.4, the micro/nano projections of barbs on porcupine quills, possessing features akin to body coat/modified hairs, are categorized as a surface domain.

2. **Mapping**: The classified biological features are intricately linked to their respective biological tissues. The outer plate of the kingfisher's beak finds its mapping to the epidermis/epithelial tissue, while the inner bone with stochastic tessellation aligns with the connective tissue [173]. In a parallel manner, the bars on the porcupine quill are associated with the keratinous material, specifically the connective tissue [158]. This mapping of biological features to their corresponding tissues enriches the comprehension and application of both the structural and material aspects of these features. It not only instigates but also ensures a systematic exploration for suitable material selection in the new design, aligning with the properties of biological materials. Refer to Figure 7.3 for a visual representation of the mapping and the materials comprising the kingfisher's beak cross-section, which include keratins, collagen, and calcium phosphate [215]. However, to render the sutures biodegradability, magnesium metal was opted for in the analysis of the sutures. Similarly, as delineated in Figure 7.5, the barbs of porcupine quills are composed of keratins [158].

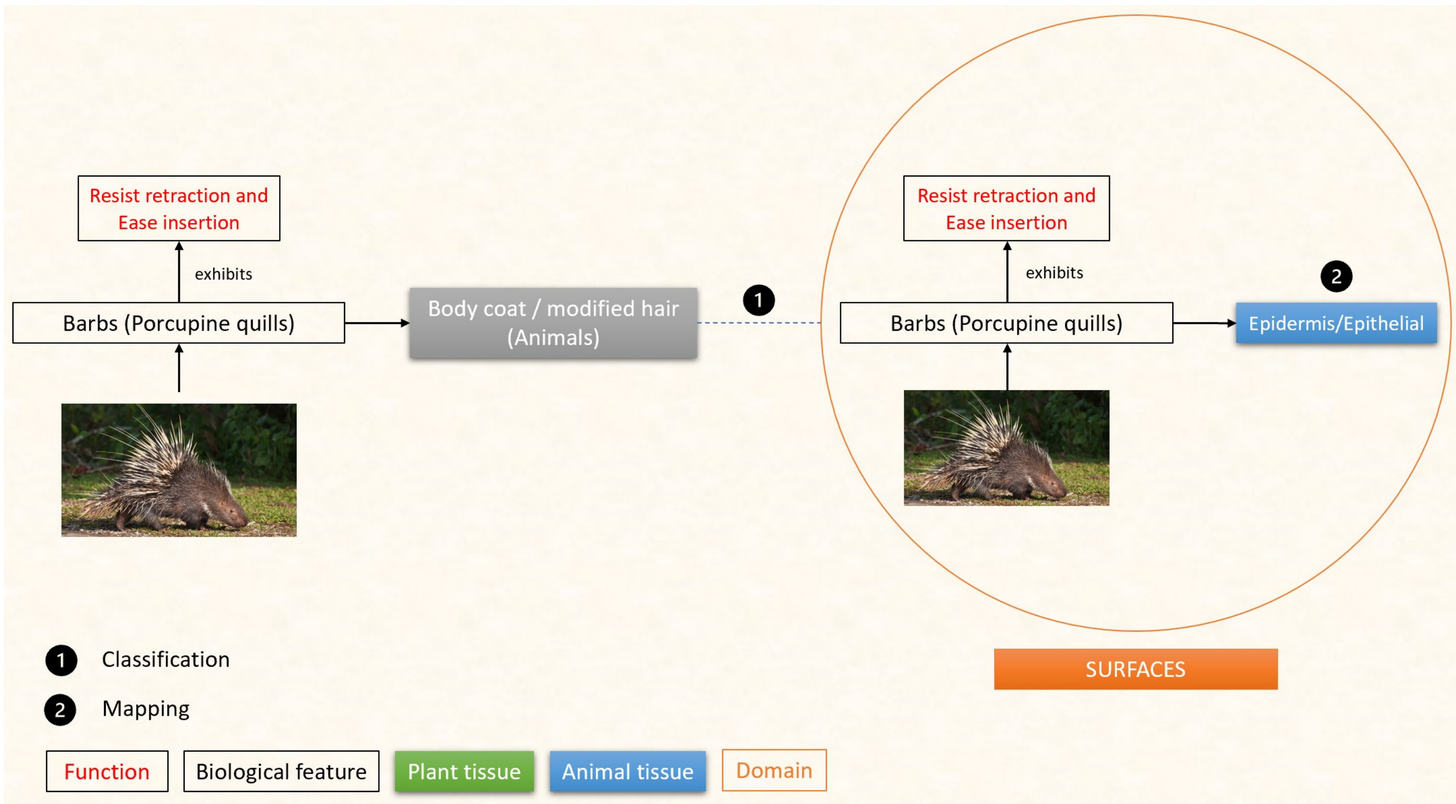


Figure 7.4: Classification and mapping of the barbs on porcupine quills to their geometric designation (Domain) and the respective tissue from which they originated.

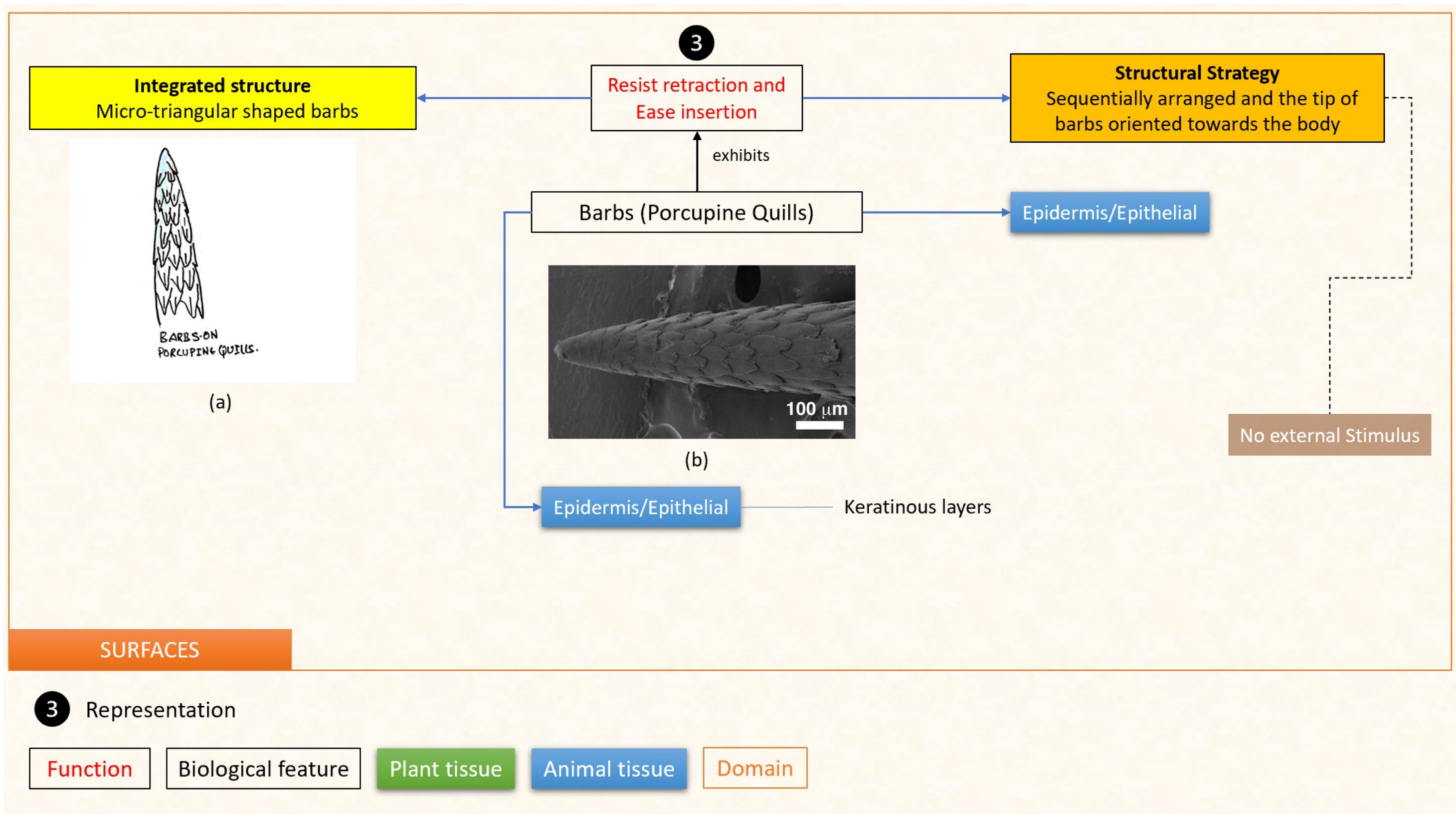


Figure 7.5: Representation of the function as a combination of integrated structure and the structural strategy. Images inspiration a) and b) [20].

3. **Representation**: Figure 7.3 and Figure 7.5 illustrates that the embodiment function of the kingfisher's beak, aimed at reducing rupture, is depicted through a composite of an integrated structure—the rotational parabolic cross-section—and a strategic structural configuration, characterized by symmetry along the axis of the beak. Simultaneously, the embodiment function of the barbs on porcupine quills, designed to resist retraction and facilitate insertion, is presented as a combination of the integrated structure—micro-triangular shaped barbs—and a strategic structural approach involving the sequential arrangement and orientation of the barbs towards the body [20].

7.1.2 Design

In this research, Rhinov6, and Autodesk Fusion-360 were used for modelling the bio-inspired suture pin-leg/needle. Table 7.1 presents the details of the dimensions of the barbs used in the design. Table 7.2 presents the dimensions of the suture pin/leg. Figure 7.6 depicts the conceptual sketch of the rotational parabolic cross-section of the kingfiher's beak and a sketch of the beak-inspired rotational parabolic cross-section structure with barbs on its surface at the moment of insertion into a tissue. Figure 7.7 depicts the con-

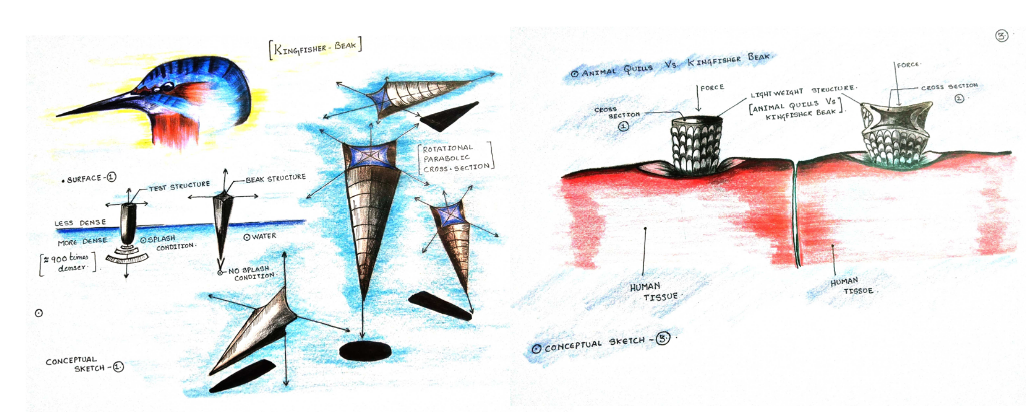


Figure 7.6: Conceptual visual of the rotational parabolic cross-section of the kingfisher's beak and the visual of the beak-inspired structure with the barbs on them at the moment of insertion.

ceptual sketch showing the difference between the conventional sutures that support wound closure and healing and the newly designed bio-inspired suture needles that support wound closure and healing. Figure 7.8 shows the

CAD models developed during the design iteration phase, the simulation was performed on Design 3 seen in Figure 7.8.

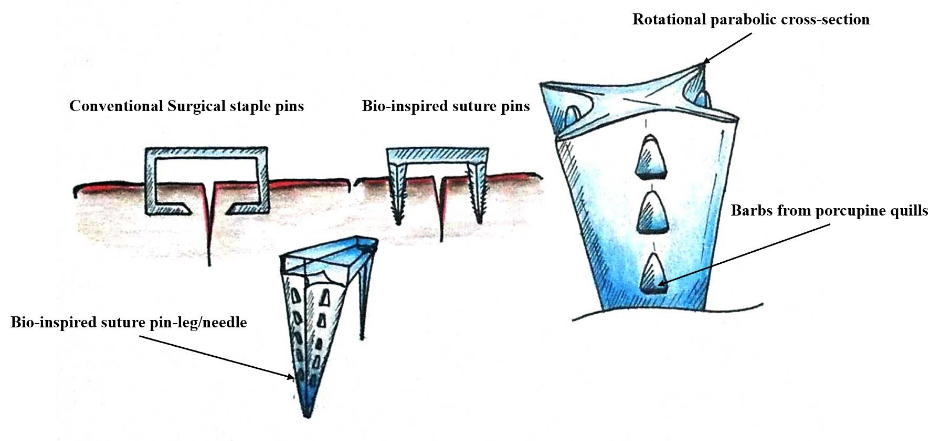


Figure 7.7: Conceptual visual of the difference between conventional needles wound healing and bio-inspired needle wound healing

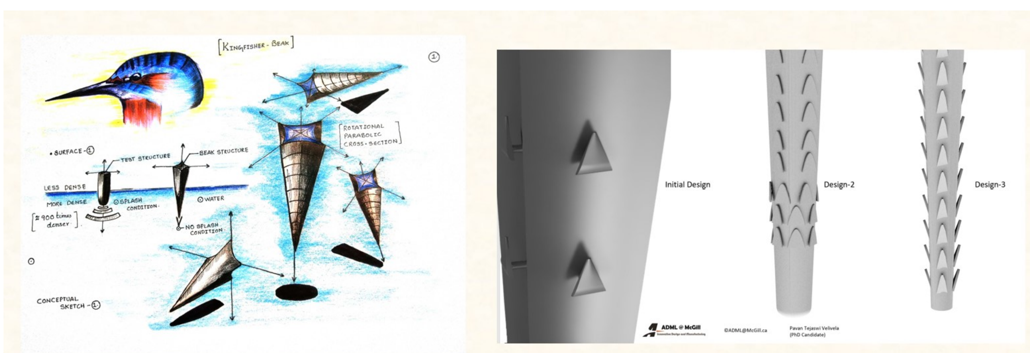


Figure 7.8: CAD model of the bio-inspired painless suture leg/pin

Table 7.1: Dimensions of the barbs used in the design

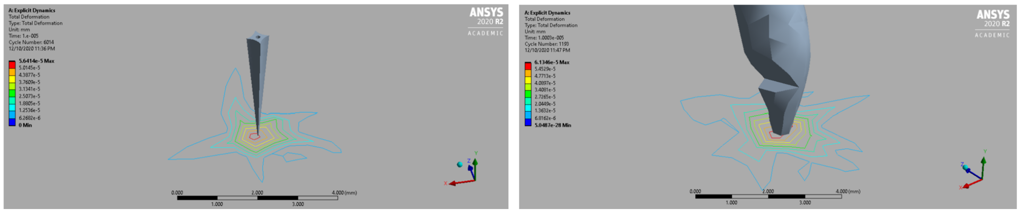
Length	**Breadth**	**Thickness**
0.1 mm	0.05 mm	0.01 mm

Table 7.2: Dimensions of the leg used in the design

Bottom tip diameter	**Circumcircle diameter at the top**	**Length of the leg**
0.02 mm	0.58 mm	3.9 mm

7.1.3 Simulation (Explicit Dynamics) and Results

Explicit dynamics simulations were conducted on the suture, excluding the barbs on the surface. This decision stems from the fact that the initial contact point is the rotational parabolic cross-sectional tip of the Kingfisher, and the barbs are not positioned at the tip of the needle. Velocities of 1 mm/sec, 2.5 mm/sec, and 5 mm/sec were assigned for both the bio-inspired suture pin leg/needle and the conventional needle. The material chosen for the conventional suture pin was Iron, consistent with the material used for the bio-inspired suture pin-leg/needle. This material choice aims to eliminate potential biases in results that may arise from using different materials in the simulation. The thickness of the epidermis layer was determined based on a study on the topography thickness of the skin on the human face [216], with an average value of 0.08 mm. Table 7.3 and Table 7.4 outline the tissue surface/epidermis deformation at velocities of 1 mm/sec, 2.5 mm/sec, and 5 mm/sec caused by the bio-inspired suture pin-leg/needle and the conventional needle, respectively.Figure 7.9 a) depicts the deformation of tissue due to the insertion of a bio-inspired suture at an insertion velocity of 5 mm/sec. Similarly, Figure 7.9 b) shows the deformation of tissue due to the insertion of a conventional needle at an insertion velocity of 5 mm/sec. Notably, the deformation of the epidermis layer is observed to be lower in the case of the bio-inspired suture pin-leg/needle tip compared to that of the conventional needle tip.



(a) (b)

Figure 7.9: a) Tissue deformation from a bio-inspired suture pin leg/needle at 5 mm/sec insertion velocity, b) Tissue deformation from a conventional suture needle at 5 mm/sec insertion velocity

Table 7.3: Results of total deformation by the impact of bio-inspired suture pin leg/needle on to the human tissue/epidermis at various velocities

S.No	**Insertion Velocities**	**Total deformation in mm (max)**
1	1 mm/sec	1.13 e-5
2	2.5 mm/sec	2.8212 e-5
3	5 mm/sec	5.641 e-5

Table 7.4: Results of total deformation by the impact of conventional suture needle on to the human tissue/epidermis at various velocities

S.No	**Insertion Velocities**	**Total deformation in mm (max)**
1	1 mm/sec	1.225 e-5
2	2.5 mm/sec	3.006 e-5
3	5 mm/sec	6.1346 e-5

7.1.4 Simulation (Static Dynamics) and Results

An axial force of 0.90 N, derived from the analysis of experiments on needle-tissue interactions discussed in section 3, was applied, and the total deformation of the needle was simulated. The point of application of the reaction force is at the needle tip, and the maximum deformation occurs at this location. In Figure 7.10 (a) and (b), the application of the reaction force on the needle is depicted in two different scenarios. The first scenario involves the force acting on the entire surface of the needle tip (case 1), while the second scenario illustrates the force acting specifically on the edge of the needle tip (case 2). In both cases the deformation is minimal and this explains that the

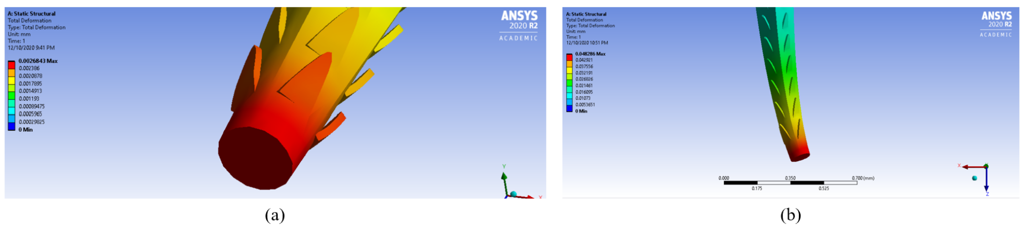


Figure 7.10: a) The deformation by application of axial (reaction due to puncture) load on the needle tip surface (case 1) b) The deformation by application of axial load (reaction force due to puncture) on the tip-edge (case 2)

structure pin is stiff enough and requires less force of insertion.

- The deformation of tissue caused by conventional suture needles is substantial, attributed to extensive surface interaction. Conversely, in the case of the bio-inspired suture pin leg/needle, a significant reduction in tissue deformation is observed.

- The augmentation of velocity yields improved results for the bio-inspired suture pin-leg/needle. This enhancement aligns with the inspiration drawn from the Kingfisher's beak, which is known for efficiently traversing from a low-density medium to a high-density medium at high velocities.

- When applying an axial force, the total deformation experienced by the bio-inspired suture pin leg/needle is minimal, indicating high stiffness. This validation supports the notion that the puncture force required for the bio-inspired suture pin/leg is considerably lower compared to that of the conventional needle.

Remarkably, in both simulations, the bio-inspired suture pin-leg/needle demonstrated superior results compared to the conventional needle.

7.2 Case-study 2:Bio-inspired multifunctional non-pneumatic tire design

Efficient friction characteristics are crucial for the design and development of automotive tires, ensuring passenger transportation safety. The braking distance of a vehicle is influenced by changes in the friction coefficient with speed [217]. Grip characteristics, dependent on the elastomer (tire) and road surface, are essential. [218] identified various factors influencing friction at the tire-pavement interface through a study of tire-pavement interactions. These factors include (a) vehicle factors encompassing load, speed, slip ratio, and camber angle, (b) tire factors involving tire type, inflation pressure, tread design, and rubber composition, (c) surface condition factors covering macro-structure, micro-structure, dryness, and wetness, and (d) environmental factors, including temperature and contamination. The increase in tangential contact stresses correlates with the rise in the friction coefficient between the tire and the road. The tangential force generated at the tire-road interface plays a pivotal role in vehicle stability and control, particularly during maneuvers and cornering. However, effective friction management in tire designs depends on the specific application for which the vehicle is designed. For instance, tire models tailored for applications like lightweight wheeled mobile robots used in military and outer space scenarios should function well in slip conditions and feature a large circumferential curvature to enhance the contact area. Tires for such applications must be non-pneumatic, featuring thread blocks, patterns, and shapes to navigate irregular terrain and execute zero-degree turns [219]. Researchers often draw inspiration from biological strategies for advanced friction management surfaces. Vincent J.F. et al [220] conceptualized a tire, inspired by a cat's soft pad and claws, for driving in icy and non-icy conditions. Tree frogs' ability to adhere to wet surfaces inspired [221] for effective wet grip development, mimicking the hexagonal columnar epithelial cells and mucus on the frogs' toepads. Ivanovic l et al [222] explored biomimetics for designing friction surfaces in tribological applications. Tires need low rolling resistance for fuel efficiency and high sliding resistance for effective braking. Commercial products like Conti PremiumContactTM, inspired by cheetah paws that widen during braking, exemplify this approach. Cheetahs narrow their paws for running to reduce friction and widen them during stops or changes in direction to increase the contact area. The quest for effective friction management surfaces persists across diverse tribological applications.

Conversely, Liu.B et al [223] introduced a saddle structure for spokes in a non-pneumatic tire, drawing inspiration from the mantis shrimp. Researchers have explored various structural innovations, such as an anti-tetrarchical gradient structure for uniform deformation to achieve vibration isolation [224], hexagonal honeycomb spokes for high fatigue resistance [225], auxetic materials for shear flexibility [226, 227], and mesostructures for achieving low rolling resistance, high shear flexure, and low-energy hysteresis loss [228]. The primary drivers for advancements in non-pneumatic tire development include lightweight construction, high stiffness for impact absorption, and enhanced flexure capabilities.

7.2.1 Design Process

The design process entails classifying, mapping, and representing biological features according to their respective geometric designations known as domains. Additionally, it involves mapping these features to the tissues from which they originate and representing the function exhibited by the feature as a combination of integrated structure and structural strategy.

1. **Classification**: Figure 7.11 illustrates that snake scales, exhibiting biological features akin to body/skin texture, fall within the surface domain. Figure 7.12 details the mapping of snake scales to their respective tissue. Similarly, Figure 7.13 depicts the woodpecker's foamy beak, showcasing biological features characteristic of stochastic tessellation, categorized under the cellular-structure domain. Figure 7.14 presents the mapping of the woodpecker's beak to its respective tissue. As indicated in Figure 7.15, the pomelo peel, displaying biological features resembling stochastic tessellation, is classified as a cellular structure.

2. **Mapping**: The identified biological features are associated with their corresponding tissues of origin. Snake scales, for instance, are mapped to the epidermis tissue containing keratin proteins [135] also shown in Figure 7.12. Similarly, the foamy layer of the woodpecker's beak, serving as an inner bone layer, is mapped to connective tissue [173]. Likewise, the stochastic structure of the pomelo peel is attributed to the formation of vascular bundles by parenchymatic tissue [165]. This mapping process guides the selection of materials for new designs that align with the properties of biological materials. For instance, snake scales are composed of keratin layers, and as shown in Figure 7.14, the

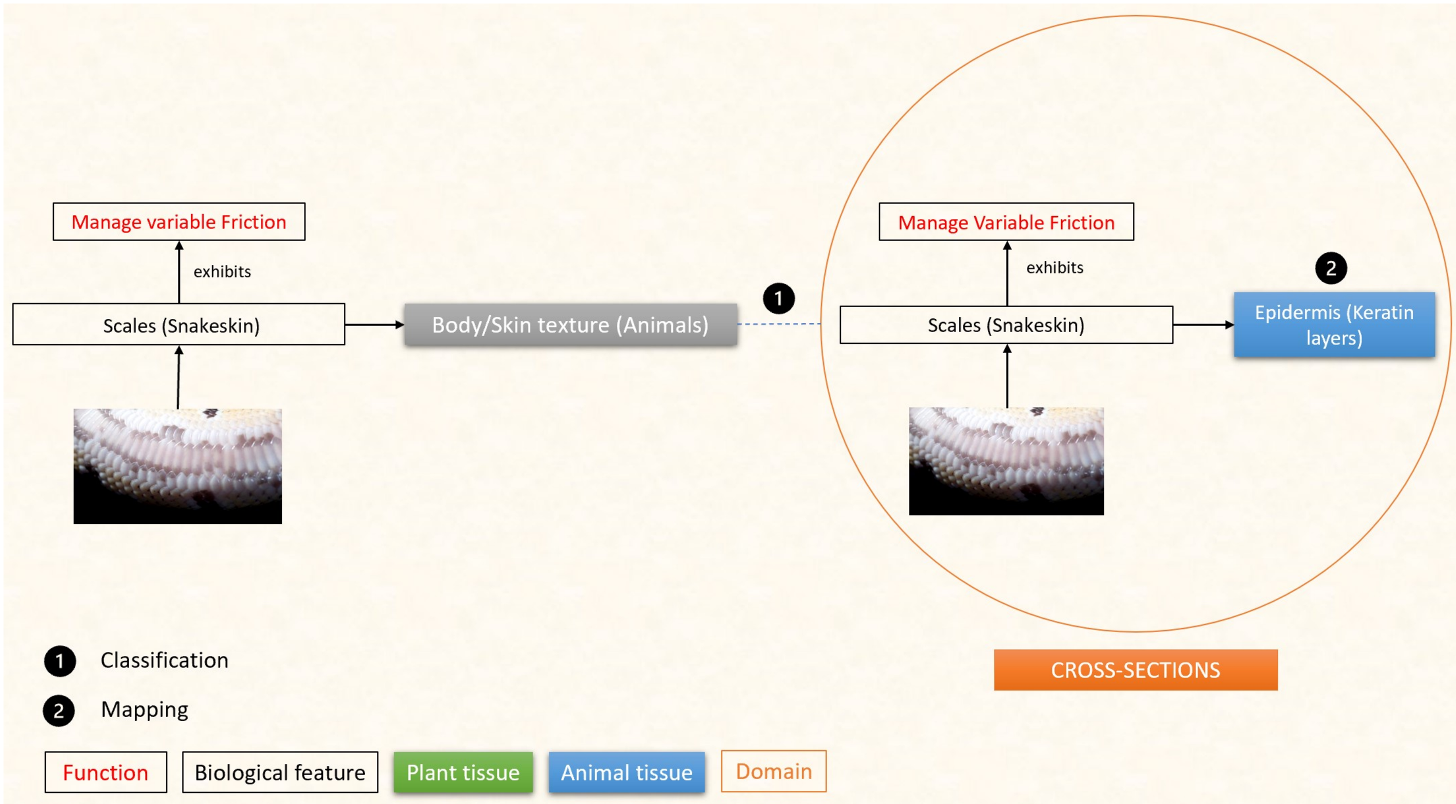


Figure 7.11: Classification and mapping of the snakeskin to its respective geometric designation (Domain) and the respective tissue from which it originated.

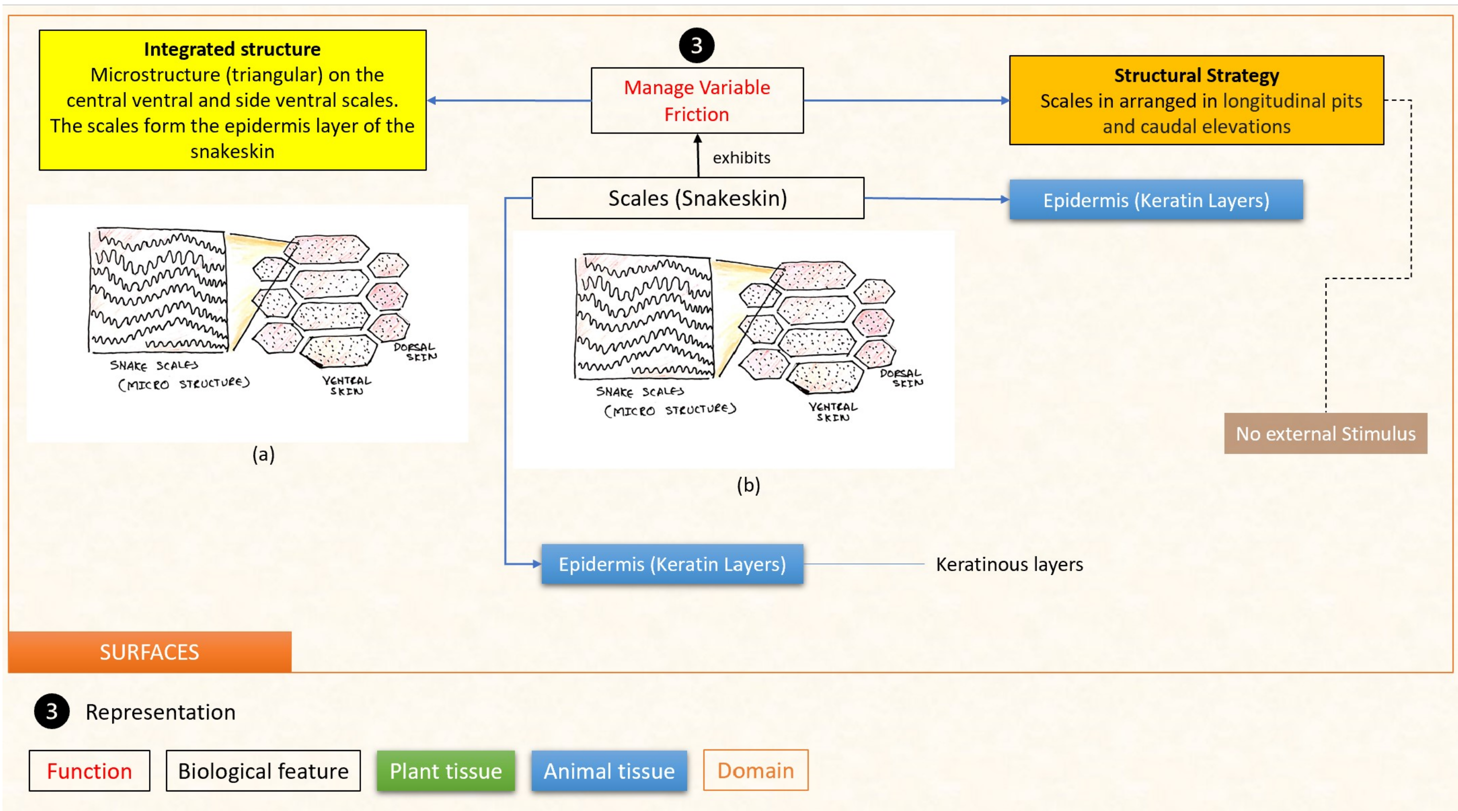


Figure 7.12: Representation of the manage friction function as a combination of integrated structure and the structural strategy. Image inspiration a) and b) [21]

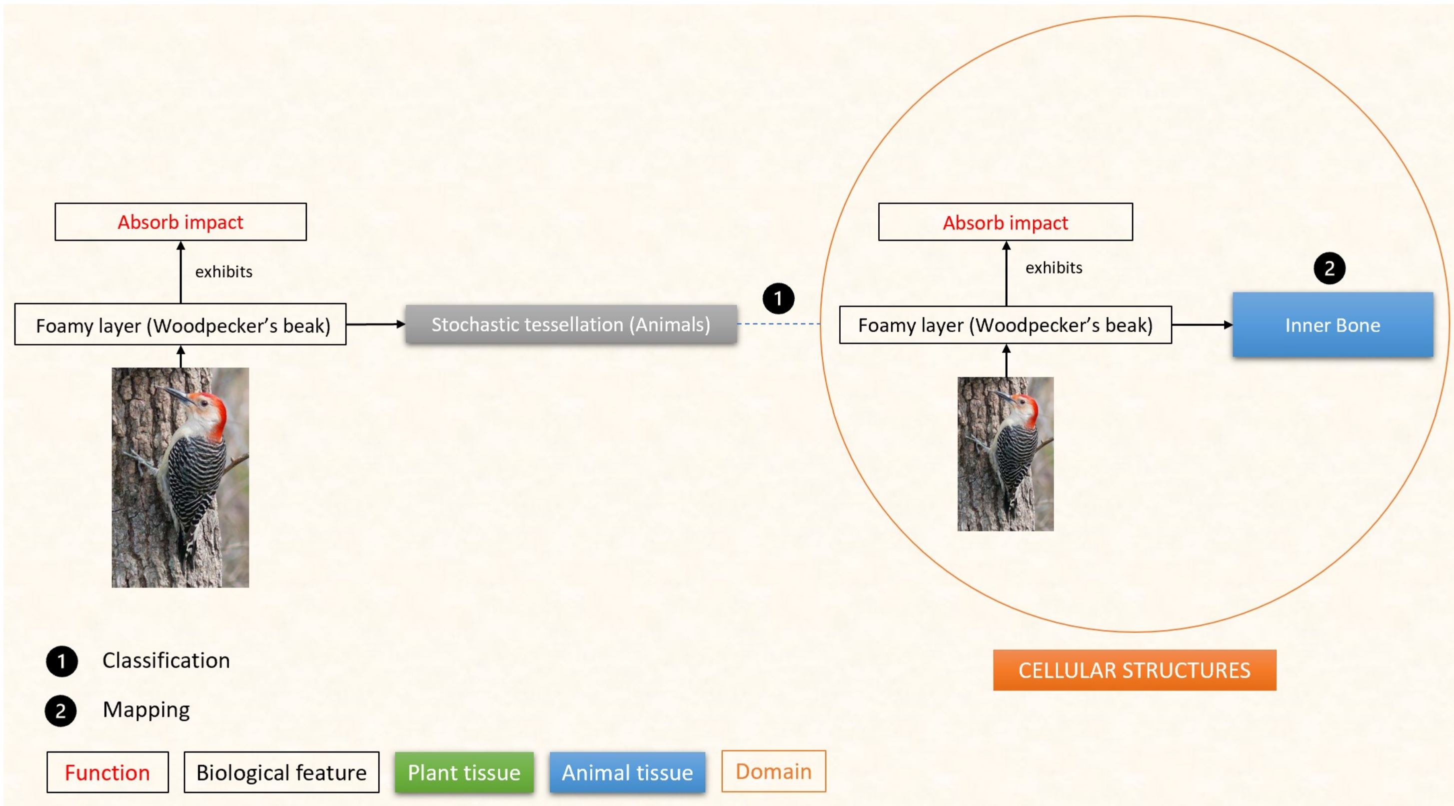


Figure 7.13: Classification and mapping of the woodpecker's beak (foam) to its respective geometric designation (Domain) and to the respective tissue from which it originated.

foamy layer consists of bundles of collagen fibers [229]. Additionally, Figure 7.16 reveals that vascular bundles comprise xylem and phloem (sieve tubes) [162]. In this study, the structural analysis performed, was focused on comparing deformation between the woodpecker's foam and the pomelo peel's foam, with the material aspect omitted

3. **Representation**: Figure 7.12 illustrate the functional embodiment of snake scales, serving to manage friction. This function is portrayed as a combination of an integrated micro-structure (triangular) on the central ventral and side ventral scales, with the structural strategy involving the arrangement of scales in caudal elevation [125]. Similarly, as shown in Figure 7.14 the embodiment function of the woodpecker's beak, designed to absorb impact, is depicted as a combination of an integrated structure—gradient foamy stochastic tessellations—and a structural strategy emphasizing the stochasticity of the foam [98]. Additionally, the embodiment function of the pomelo peel, as depicted in Figure 7.16, intended to absorb impact, is presented as a combination of an integrated porous structure and a structural strategy involving the stochastic arrangement of dense vascular bundles [165].

7.2.2 Design

Figure 7.17 depicts the schematic sketch of a multi-functional non-pneumatic tire design, drawing inspiration from snakeskin for effective friction management and incorporating features from the woodpecker's beak and pomelo peel for impact resistance. Figure 7.18 depicts the conceptual sketch detailing the anisotropic nature of the snakeskin on the surface of the tire which enhances the effective friction management between the tire and the road. Figure 7.19 showcases the conceptual sketch of the tire with the impact-resistant porous gradient structures inspired by the woodpecker's beak and pomelo peel. The woodpecker's beak exhibits varying porosity, starting at 30 percent at the tire interface, increasing to 65 percent in the middle, and returning to 30 percent at the central region. Similarly, the pomelo peel features variable porosity—40 percent at the tire interface, 50 percent in the middle, and 30 percent at the central region. To assess impact resistance, understanding the tire-pavement interaction is crucial. Unlike pneumatic tires with elliptical patches, non-pneumatic tires have rectangular patches [230]. Therefore, modeling and analysis focus on these patches rather than the entire tire. Notably, the research excludes modeling and analyzing the snake-inspired

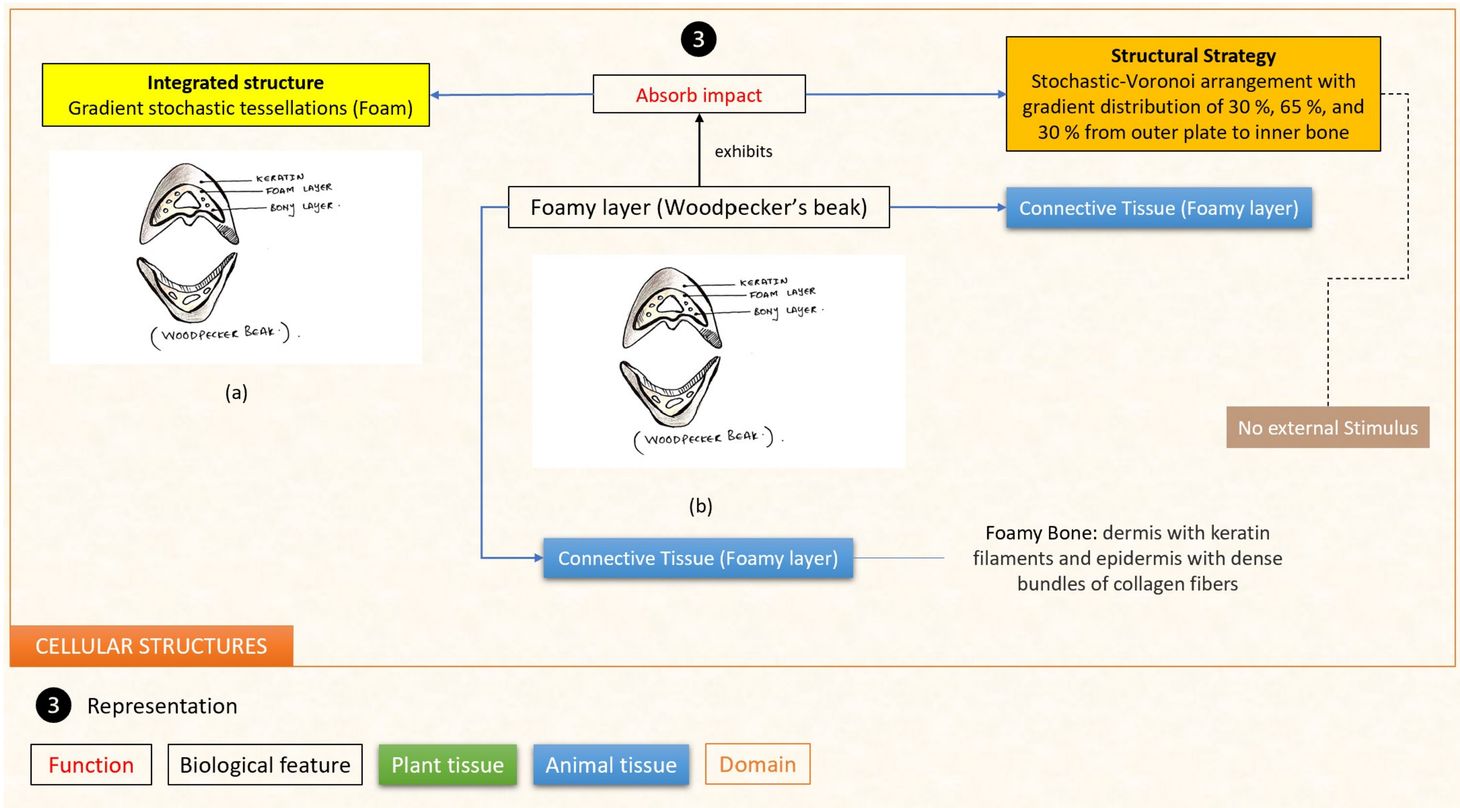


Figure 7.14: Representation of the woodpecker beak function as a combination of integrated structure and the structural strategy. Image inspiration a) and b) [22].

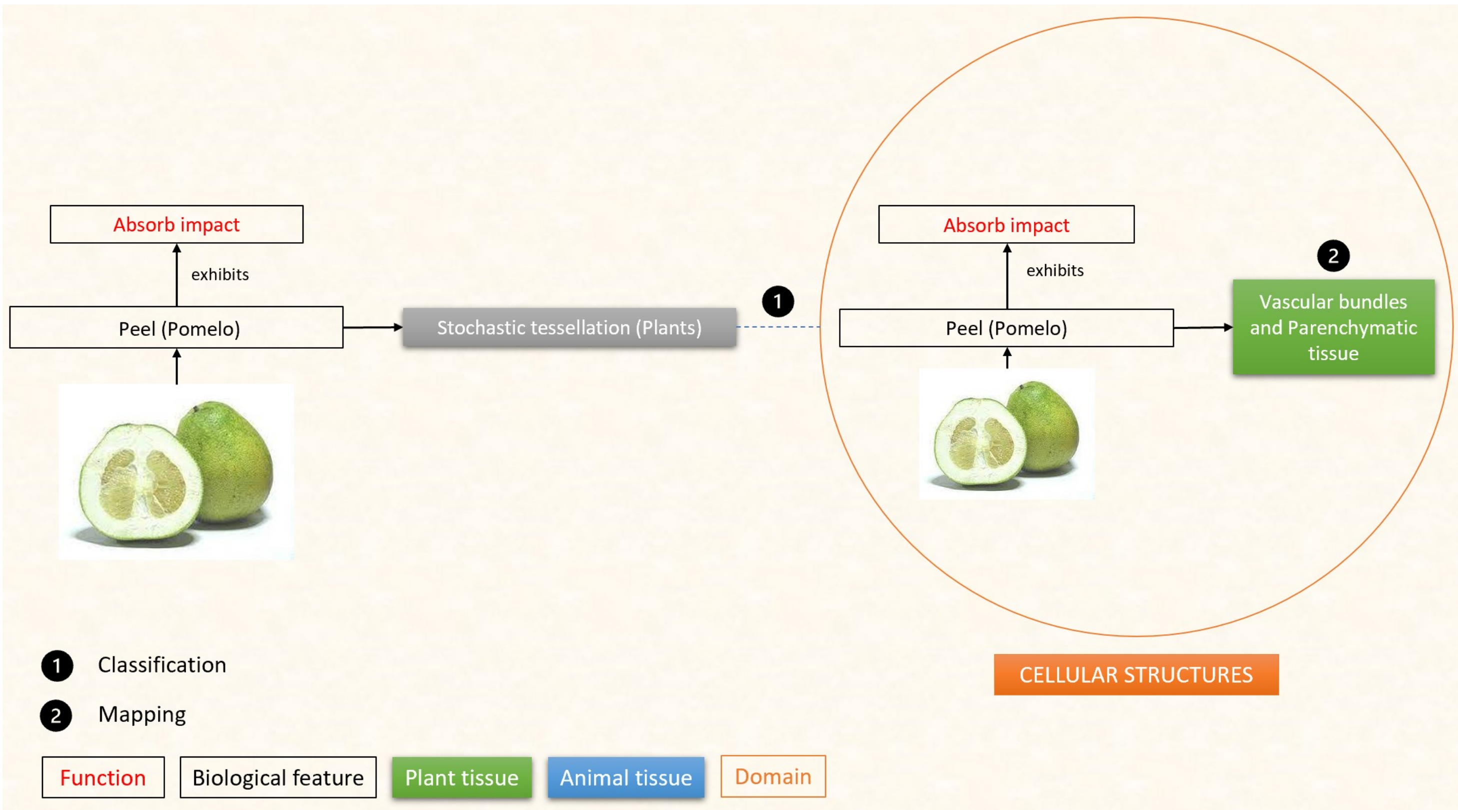


Figure 7.15: Classification and mapping of the pomelo peel (foam) to its geometric designation (DOmain) and to the respective tissue from which it originated.

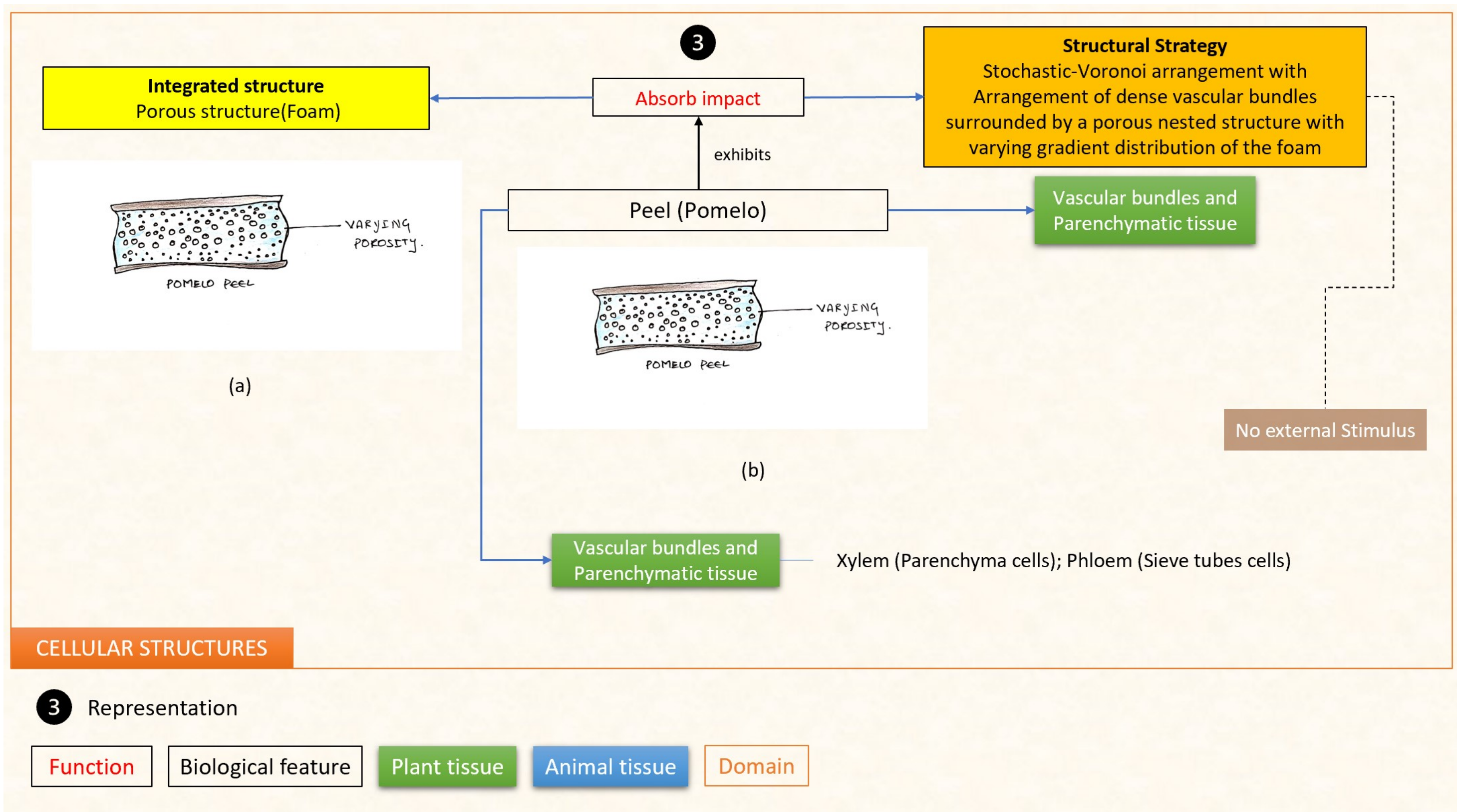


Figure 7.16: Representation of the absorb impact function of pomelo peel as a combination of integrated structure and the structural strategy. Image inspiration a) and b) [16].

texture, aiming instead to validate meta-level parameters for selecting appropriate biological analogies and addressing the convergent evolution problem.Figure 7.20 showcases the conceptual sketch of the patches (sections) of the tire that are simulated to compare the impact resistance between the woodpecker-inspired structure and pomelo peel structure. Table 7.5 provides the details of the function, biological feature, the description of the structure, meta-level design parameter verified and the Domains to which they were assigned.

Table 7.5: Functions, Biological system, Meta-level design parameter, and respective Domains

Function	**Biological Feature**	**structure**	**Meta-level design parameter**	**Domain**
Efficient friction management	Snakeskin	Microstructur (triangular) on the central ventral and side ventrals [21]	Interaction area and Scale	Surfaces
Impact resistant	Pomelo peel	Porous hierarchical structure [101]	Interaction area and Porosity	Cellular Structures
Impact resistant	Woodpecker's beak	The hyoid bone, carnal bone, and beak bone contain a hierarchical composite structure [98]	Interaction area and Porosity	Cellular Structures

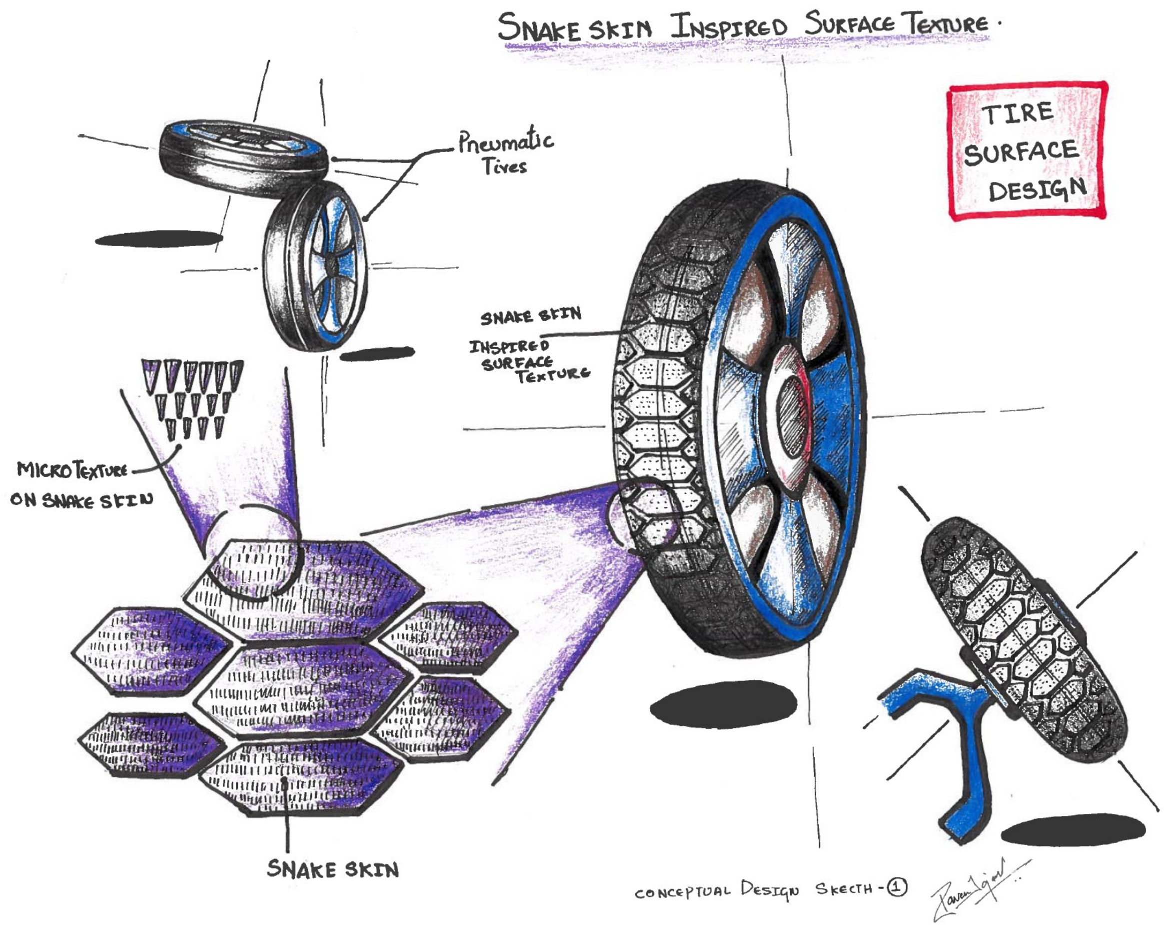


Figure 7.17: Conceptual visual of the surface of the non-pneumatic tire inspired by snakeskin

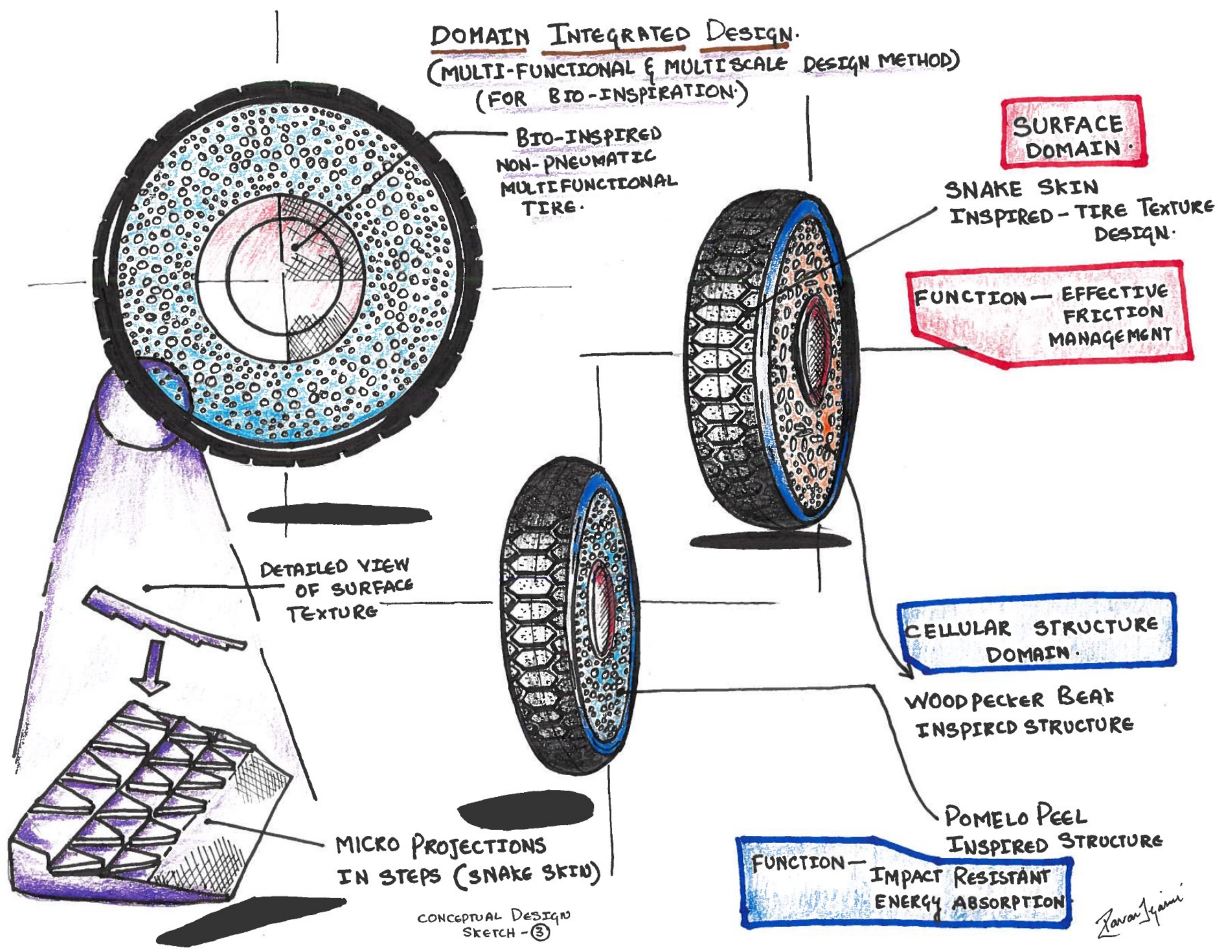


Figure 7.18: Conceptual visual of the details of the anisotropic nature of the snakeskin

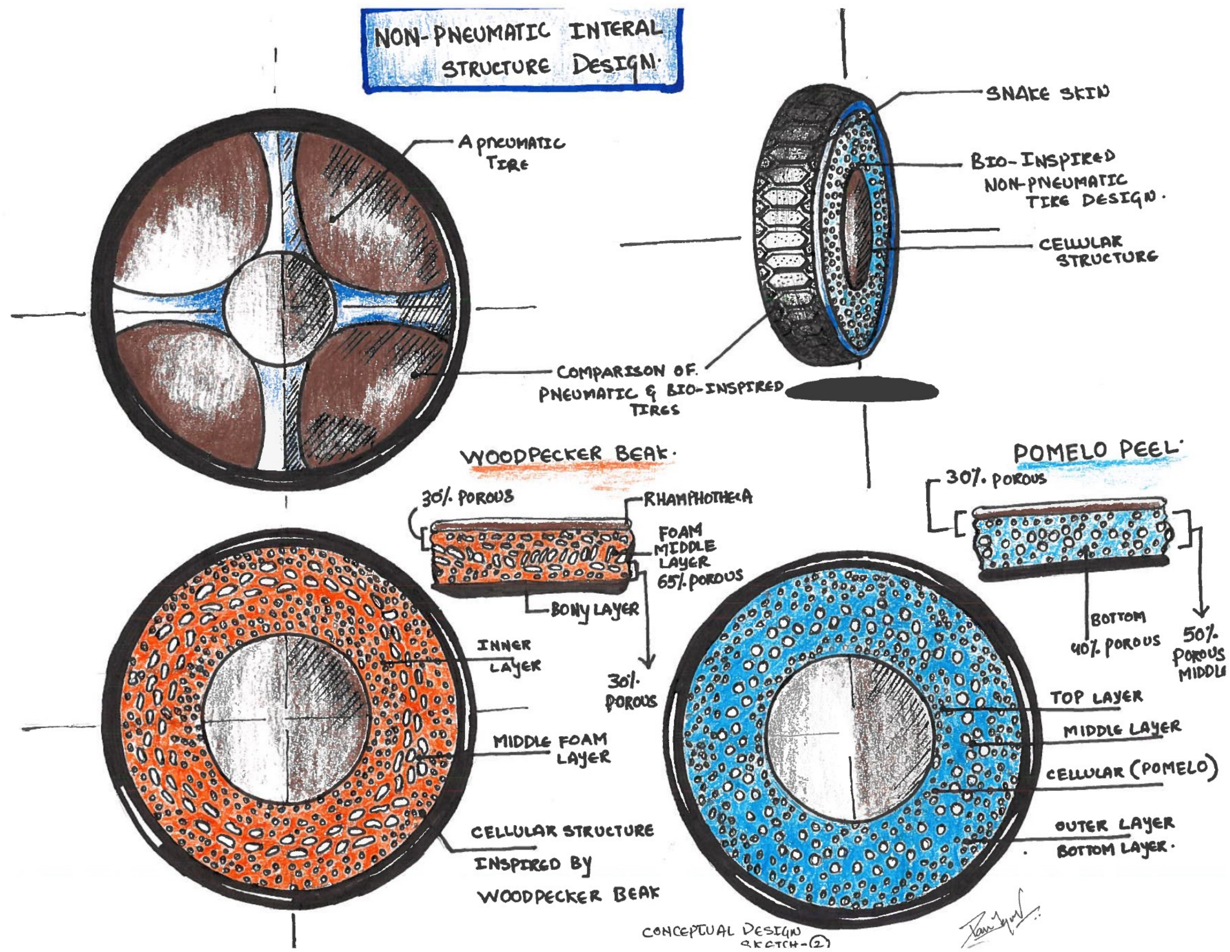


Figure 7.19: Conceptual visual of the non-pneumatic tire design with impact resistance structures inspired by woodpecker's beak and pomelo peel

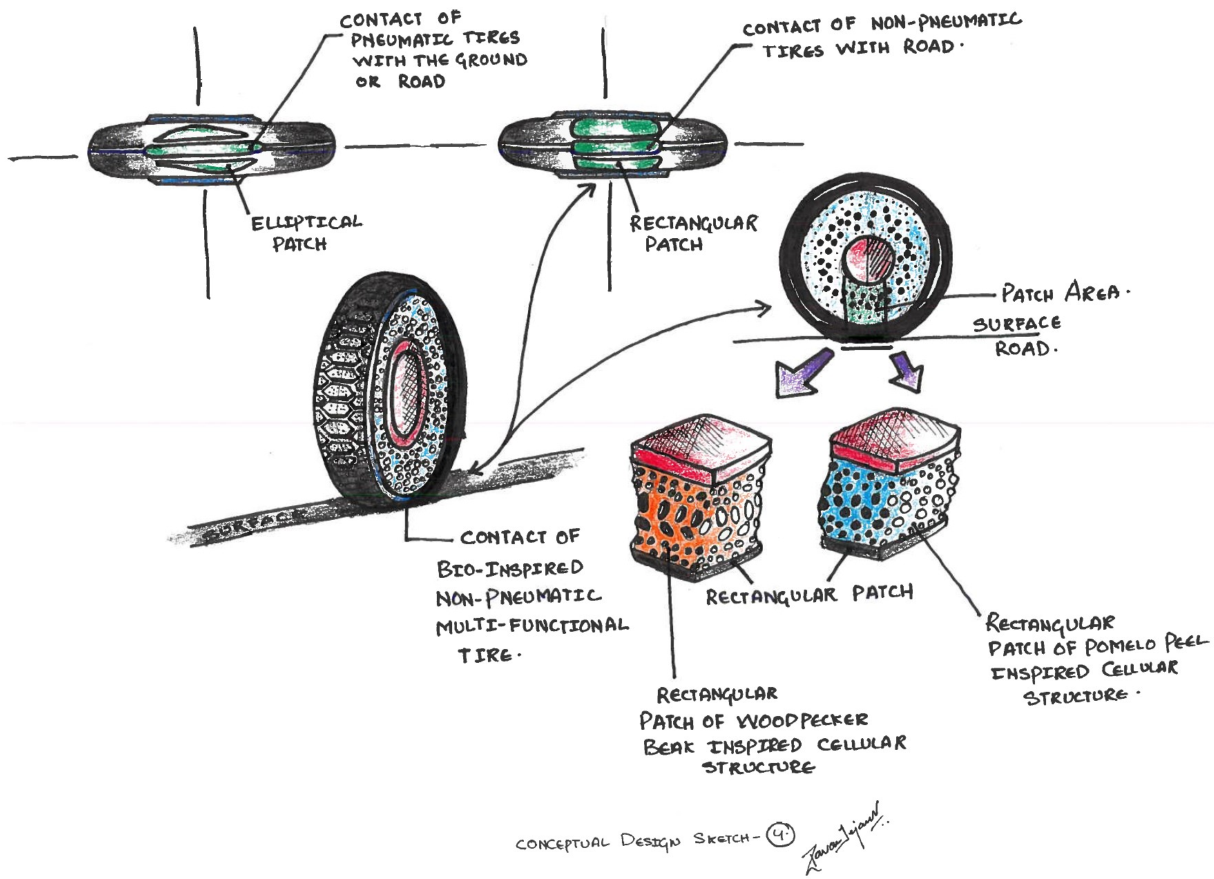


Figure 7.20: Conceptual visual of the sections of non-pneumatic tires chosen for computer simulation

Geometric Modelling

Various lattice topologies can be employed to approximate the original conceptual design, with the Schwarz Primitive (Schwarz P) surface topology closely resembling the intended design. In this study, the lattice modeling approach from a previous work [231] was chosen. This approach enables geometric modeling of lattice structures based on triply periodic minimal surfaces (TPMS) with adjustable parameters. The framework for this approach has been integrated into the open-source software LatticeQuery [232].

Figure 7.21 depicts a sketch where O represents the location of the tire axis, and r_I, r_{II}, and r_{III} signify the upper limits of regions I, II, and III, respectively. These regions have different porosities to closely mimic their natural analogues.

For the woodpecker-inspired design, the porosities (φ) in regions I, II, and III are $\varphi_{w_I} = \varphi_{w_{III}} = 30$ percent, and $\varphi_{w_{II}} = 65$ percent. For the pomelo-inspired design, the porosities $\varphi_{p_I} = 40$ percent, $\varphi_{p_{II}} = 50$ percent, and $\varphi_{p_{III}} = 30$ percent. The decision to use a base unit cell size of u=3.98 mm was made to accommodate a significant number of unit cells in the lattice.

Woodpeckers have a porous region corresponding to region II elongated in the load direction, so unit cells in the woodpecker region II were elongated by 50 percent in the r-direction. While LatticeQuery supports setting variable thickness t in a specific direction, it does not directly support varying porosity φ. The 3D print plugin in Blender validated the lattice thickness, providing a proper estimate of the volume [233]. It was determined that the porosities $\varphi_{w_I} = \varphi_{w_{III}} = \varphi_{p_I}$ =30 percent can be ensured with t=1.34 mm; $\varphi_{w_{II}}$ =65 percent with t=0.61 mm; $\varphi_{p_{II}}$ =50 percent with t=0.89 mm; and $\varphi_{p_{III}} = 40$ percent with t=1.10 mm.

7.2.3 Simulation and Results

The stereolithography (STL) mesh was simulated using FEM in Abaqus Standard Edition 2021 for the conceptual tire design. Typically, a contact patch of the tire experiences loads around 2100 N [234]. As only one column is analyzed, this load is distributed across $45 \times 11 = 495$ unit cells, resulting in a 4 N load per column. Considering a safety factor of 1.125 for the tire load [235], the load per column is adjusted to 4.5 N. Elongation, a key characteristic for tire analysis [236], was chosen as a focus. Rigid polyurethane was selected as the simulation material.

Figure 7.22 a) and Figure 7.22 b) display the results of the FEM sim-

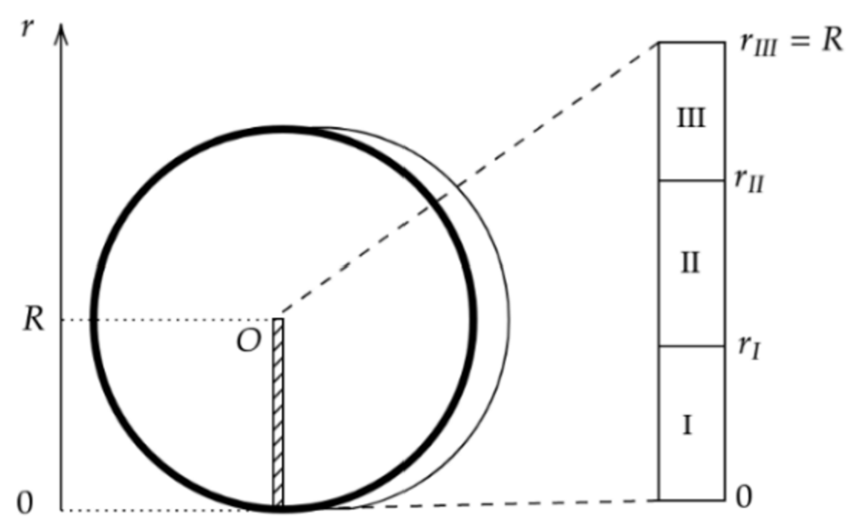


Figure 7.21: A single column is split into three regions resembling the actual porosities observed in biological analogies

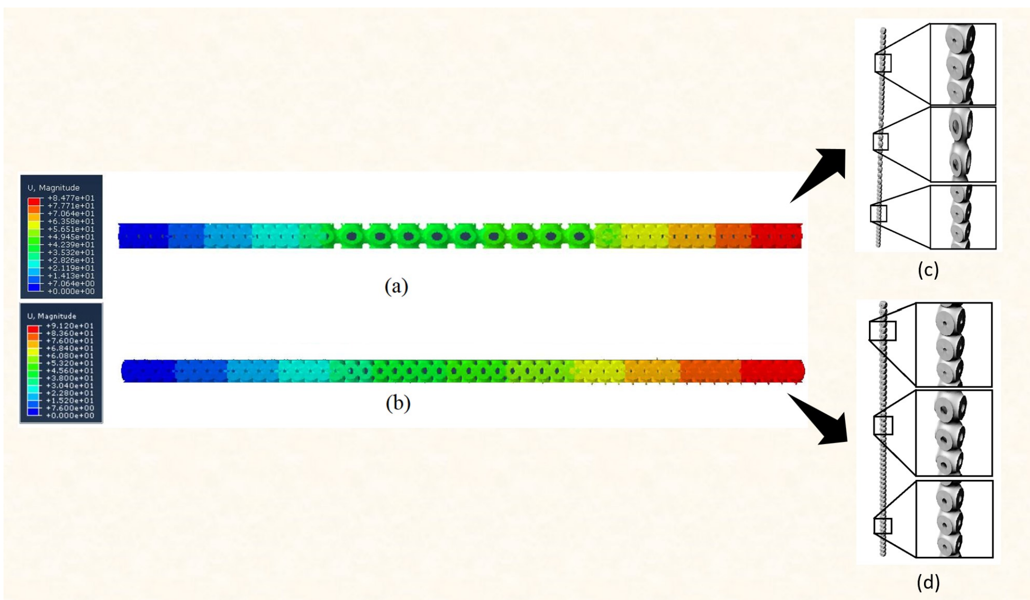


Figure 7.22: Static analysis performed on a single column of the woodpecker's beak and pomelo peel.

ulation for single columns corresponding to the woodpecker- and pomelo-inspired designs, respectively. The maximum deformation magnitudes are 84.77 and 91.20 for the woodpecker- and pomelo-inspired designs, respectively. These values are significantly below the estimated elongation at break, anticipated to exceed 200 [237]. Notably, the region directly in contact with the road surface (Region I) exhibits the highest deformation, aligning with expectations from the conceptual design phase. This motivated providing Region I with lower porosity than the other two regions, enhancing material interaction and consequently reducing deformation.

Table 7.6: Comparison of the impact resistance of woodpecker's beak and pomelo peel concerning its interaction area with the porosity

Biological system	**Interaction Area**	**Porosity**	**Result**
Woodpecker's beak	High	Low	High Impact resistance
Pomelo peel	Medium	Medium	Medium Impact resistance

The woodpecker's beak exhibits low porosity in Region I, directly in contact with the road, resulting in a higher interaction area and consequently lower deformation. This simulation affirms the initial hypothesis, advocating the selection of features with a higher interaction area and low porosity for applications involving adsorption/absorption functions. Table 7.6 compares the interaction area and porosity of the woodpecker's beak and pomelo peel.

7.3 Case-study 3:Bio-inspired effective heat transfer and low-pressure drop structures for aerospace applications

In this study, for achieving low-pressure drop and highly effective convective heat transfer, inspiration is drawn from two biological sources belonging to different domains: the camel turbinate from the cross-section domain and the Namib Desert beetle micro bumps from the surface domain. Camels, thriving in hot, arid environments, employ two principles to enhance heat transfer for cooling: firstly, the evaporation of surface water droplets lowers the air temperature, and secondly, a greater surface area increases the rate of evaporation or condensation [238]. The camel nasal cavity features intricate turbinates—narrow, highly scrolled air passageways—creating a large surface area for water exchange and heat transfer [23,238,239]. Moisture exchange is facilitated by a mucus membrane on the surface of the turbinate [238]. In the current application, the camel turbinate structure serves as inspiration for a geometry with a large surface area for heat transfer while simultaneously minimizing pressure loss. Namib desert beetles, adapted to arid conditions, feature micro bumps on their outer surface with a hydrophilic wax coating, enabling them to absorb water vapor from the surrounding air. For the present study, the focus is on assessing the structural topology, omitting consideration of the camel turbinates' mucus membrane and the Namib desert beetle's hydrophilic wax coatings. In the combustor, where high temperatures result in low relative humidity, micro bumps, and dents are introduced to augment the surface area and enhance effective heat transfer. Additionally, a projection between the turbinate layers is incorporated to boost air-surface interactions.

7.3.1 Design Process

Similar to the previous case studies, the design process entails classifying, mapping, and representing biological features according to their respective geometric designations known as domains. Additionally, it involves mapping these features to the tissues from which they originate and representing the function exhibited by the feature as a combination of integrated structure and structural strategy.

1. **Classification**: In Figure 7.23, the cross-sectional view of camel turbinates exhibits biological characteristics akin to a cross-section of the nasal cartilage, falling within the domain of cross-section. Figure 7.24 illustrates the correlation between camel turbinates and their corresponding tissue mapping. Likewise, Figure 7.25 depicts the micro/nano projections of the Namib Desert beetle, showcasing biological features resembling body/skin texture and falling into the surface domain.

2. **Mapping**: The identified biological features are linked to their respective tissues of origin. The camel's turbinate, specifically the nasal cartilage, aligns with connective tissue [23]. Similarly, the micro/nano projections of the Namib Desert beetle are associated with the epicuticle/epidermis tissue [123]. Figure 7.24 details this mapping, highlight-

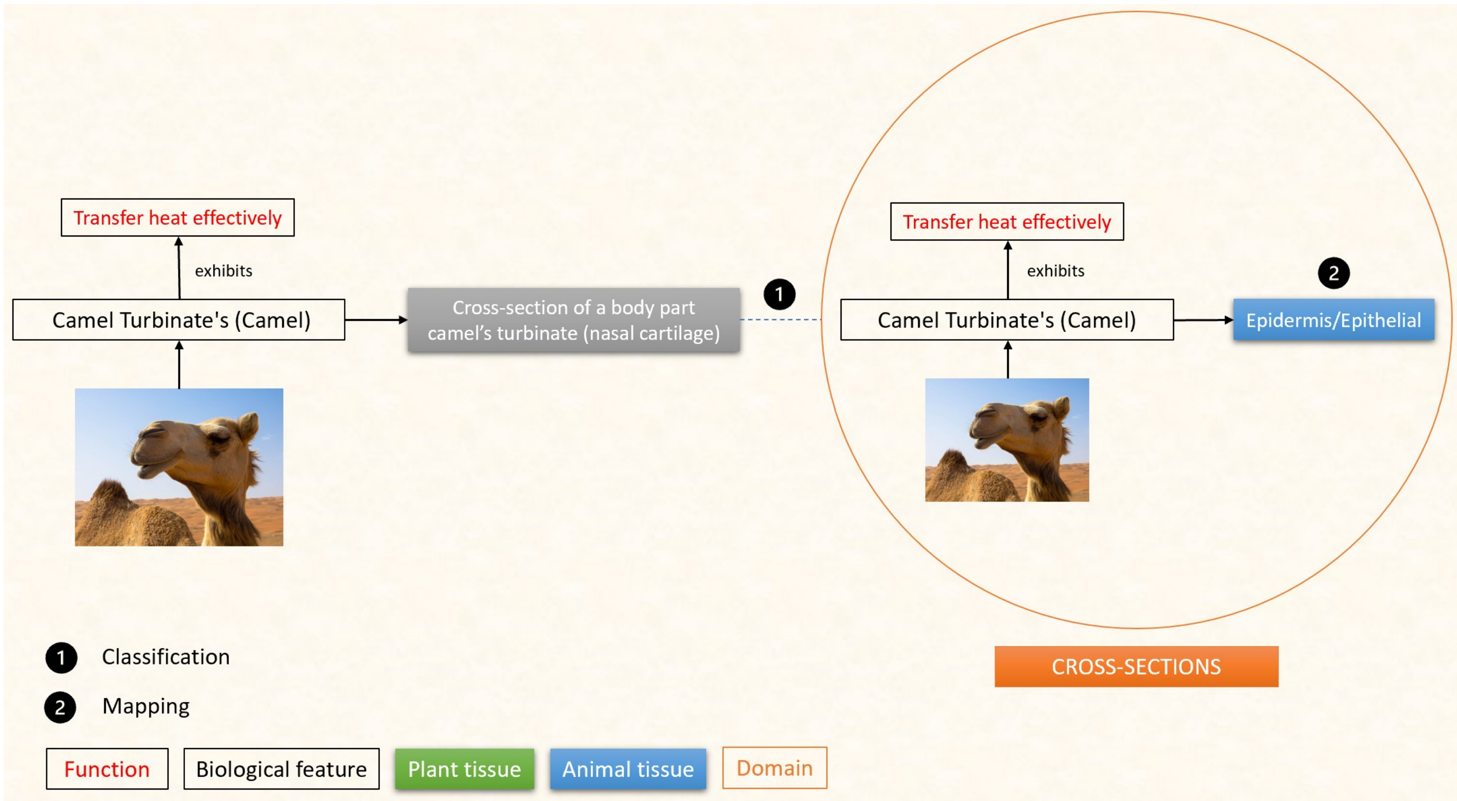


Figure 7.23: Classification and mapping of the camel turbinate (cross-sections) to its geometric designation (Domain) and the respective tissue from which it originated.

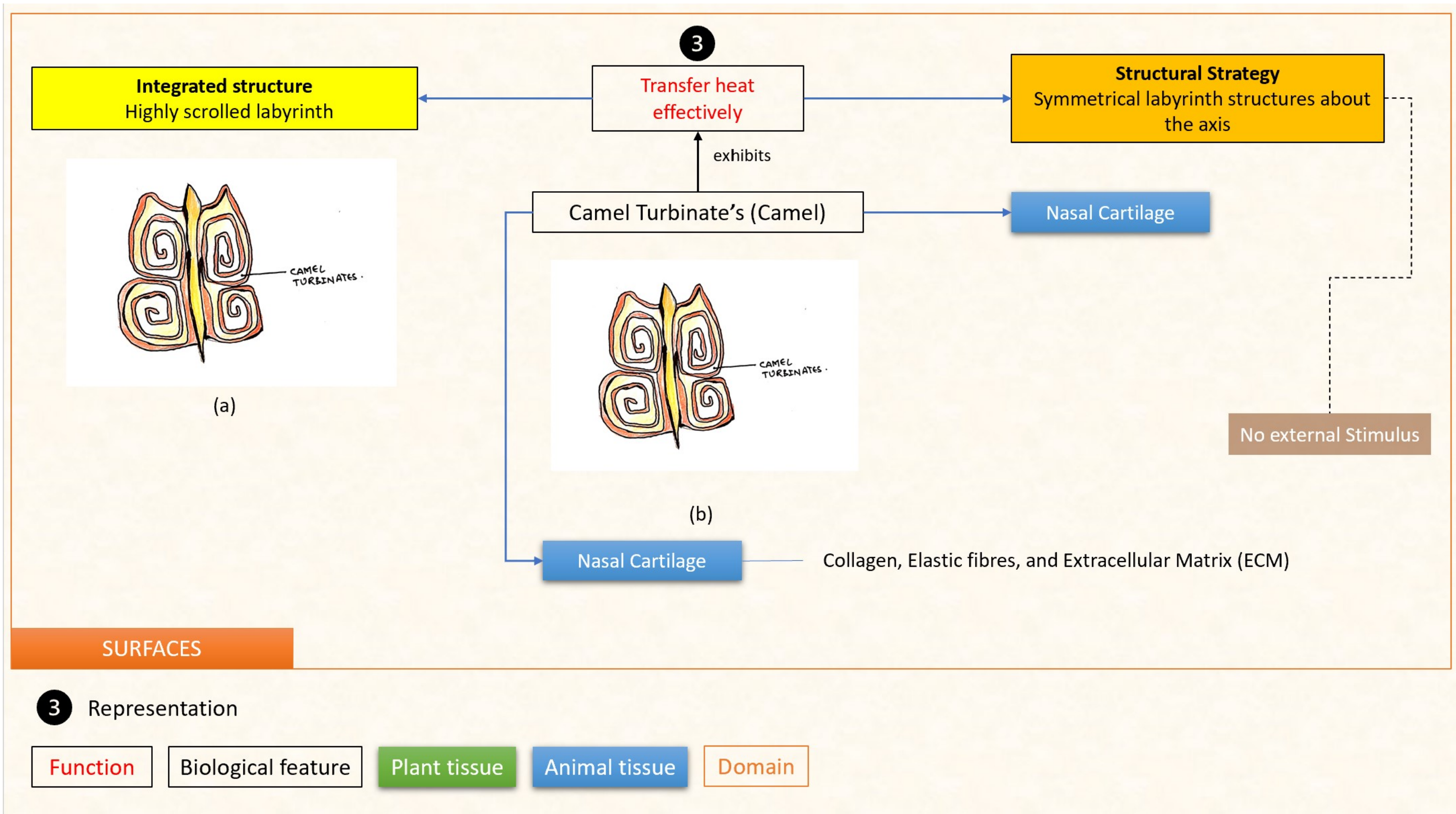


Figure 7.24: Representation of the camel turbinate function as a combination of integrated structure and the structural strategy. Image inspiration a) and b) [23].

ing the materials constituting each tissue. This mapping process serves as the foundation for selecting suitable materials in the design phase that mirror the properties of biological materials. For instance, nasal cartilage comprises collagen, elastic fibers, and extracellular matrixes (ECM) [240], as illustrated in Figure 7.24. Similarly, Figure 7.26 shows that the micro bumps of the Namib Desert beetle result from the keratin layers of the skin. In this study, the focus is on analyzing structures for convective heat transfer, with the material aspects omitted.

3. **Representation**: Figure 7.24 and Figure 7.26 illustrate the functional embodiment of the camel turbinate structure, serving the purpose of heat transfer. This function results from a combined integrated structure—specifically, a labyrinth [23, 238]—and a structural strategy involving symmetry along the axis. Similarly, the embodiment function of the Namib Desert beetle's micro bumps, designed to increase surface area and absorb water, is depicted as a combination of an integrated structure. In this case, the peaks exhibit hydrophilic properties, the valleys are hydrophobic, and the structural strategy involves orienting the micro bumps at 23 degrees to the ground [123].

7.3.2 Designs

In Table 7.7, the biological inspiration, feature domain, and feature functions are outlined. The dimensions of the generated structures are adjusted to fit a combustor's dimensions. The design is modified from a turbinate (camel's intricate loop structure) to concentric circular sections to accommodate the simulation setup. Internal projections are added to enhance air interaction with the structure. As shown in Figure 7.29, four structures were generated and simulated. The first structure combines concentric circular sections and micro bumps inside each section (Turbinate + Bumps - TB). The second structure combines concentric circular sections and micro dents inside each section (Turbinates + Dents - TD). The third structure combines concentric sections, micro bumps, and internal projections (Turbinates + Bumps + Internal Projections - TBP). Finally, the fourth structure combines concentric circular sections, micro dents, and internal projections (Turbinate + Dents + Internal Projections - TDP). Figure 7.27 showcases the conceptual sketch of the camel-inspired intricate turbinates which are highly scrolled passageways that have a large surface area of interaction for effective heat transfer and low-pressure drop. Also, Namib desert beetle-inspired micro-bumps further

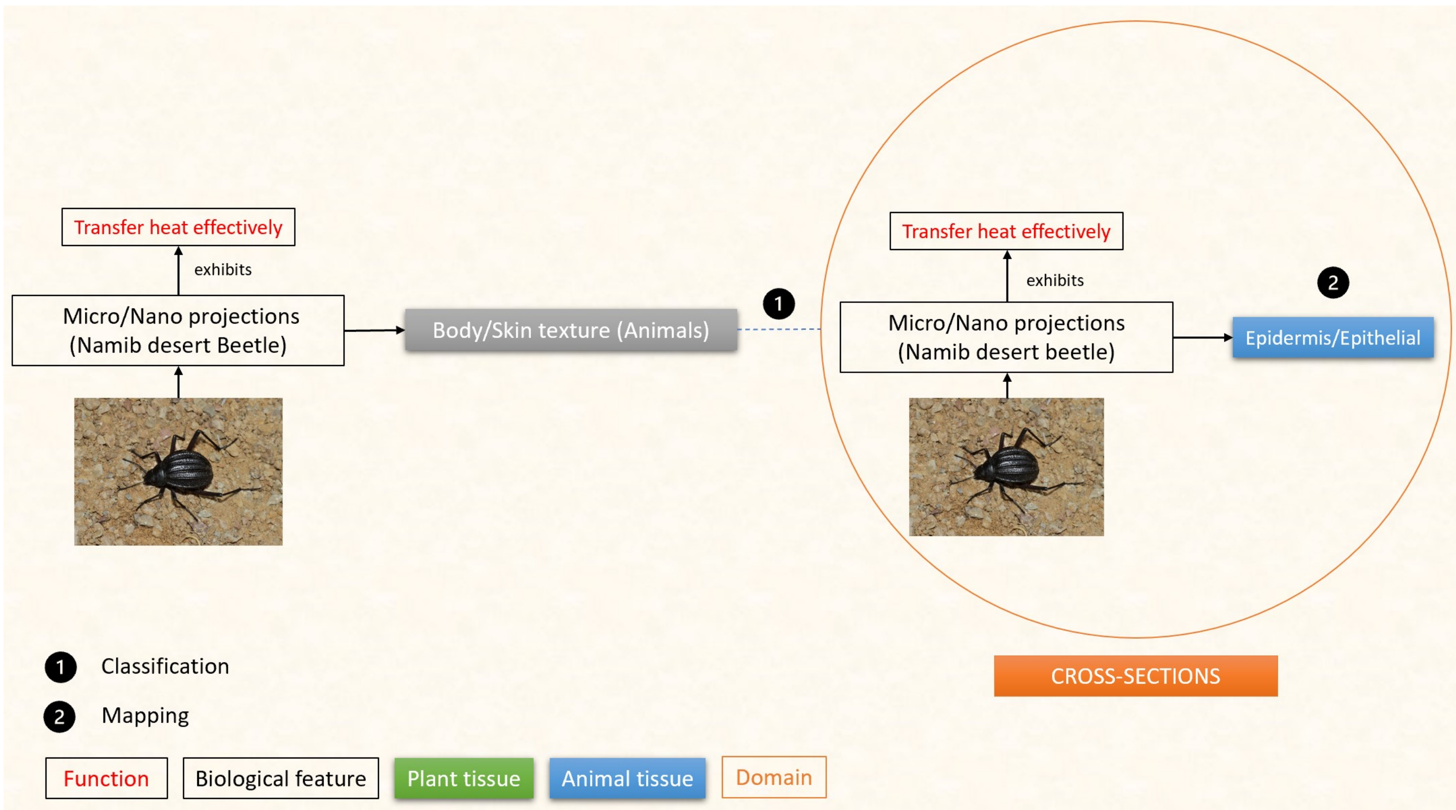


Figure 7.25: Classification and mapping of the Namib Desert beetle's surface to its respective domain and the tissue from which it originated.

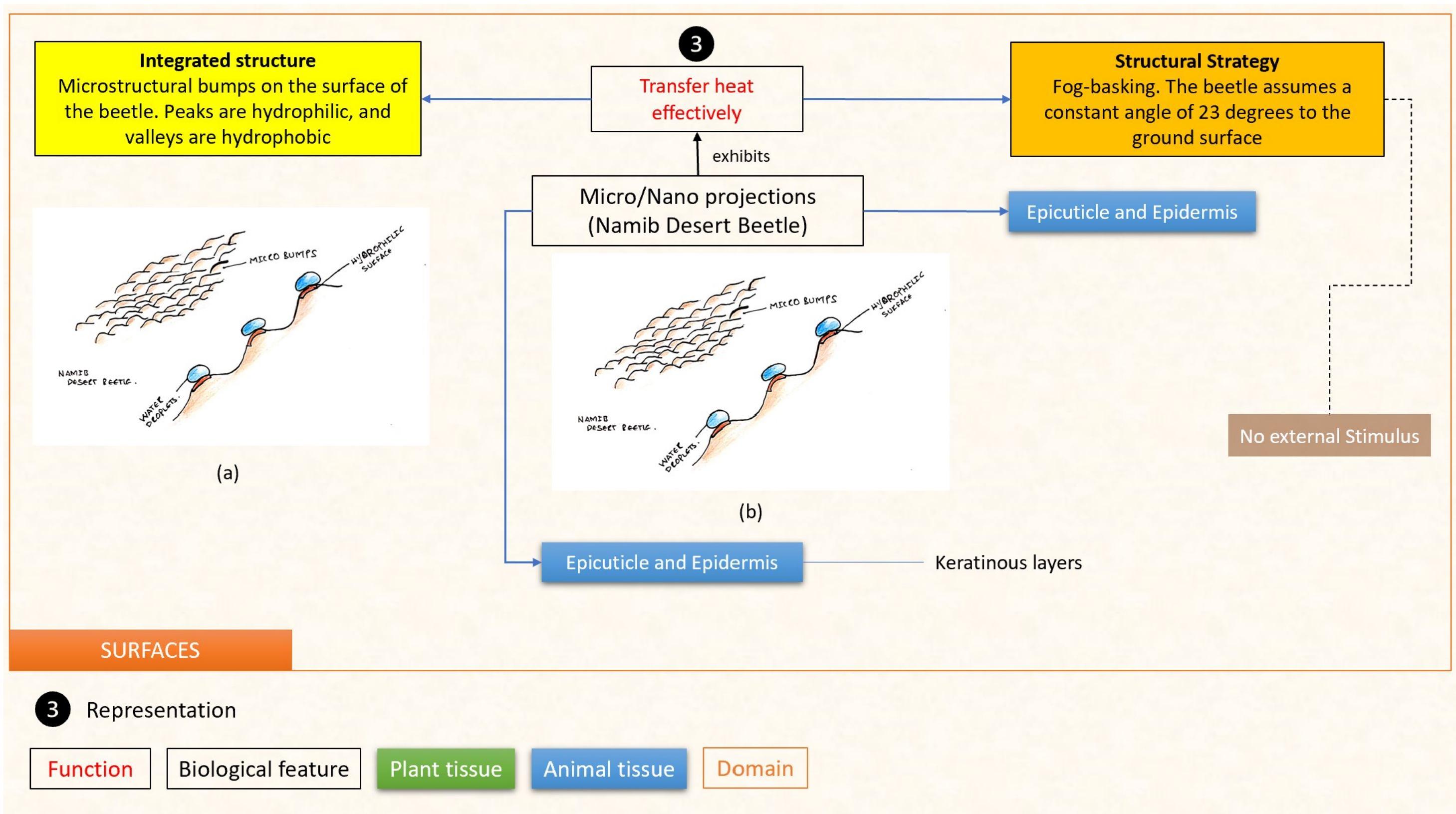


Figure 7.26: Representation of the function as a combination of integrated structure and the structural strategy. Image inspiration a) [24], and b) [25].

increase the surface area of interaction. Figure 7.28 presents the CAD models developed integrating the turbinate structures and the micro-bumps on the surface. The initial design is a highly scrolled loop structure with micro-bumps and the final design is concentric circular sections with micro-bumps on each concentric circular section.

Table 7.7: Biologically inspired structures from different Domains for integration and generation of multifunctional structures

Bio-inspiration	**Domain**	**Function**
Camel turbinates [238]	Cross-sections	Effective cooling and reduced pressure loss
Namib desert beetle [123]	Surfaces	Water absorption

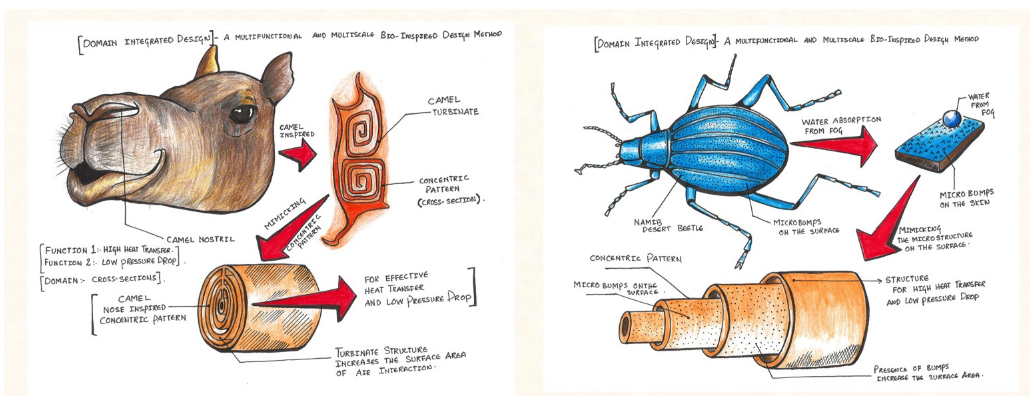


Figure 7.27: Conceptual visual of the camel turbinates structure and the Namib desert beetle micro-bumps for effective heat transfer and low-pressure drop applications.

7.3.3 Simulation and Results

Computational Fluid Dynamic (CFD) analysis was performed on all the bio-inspired designs and was compared with the conventional lattice structures. For the simulation, tetrahedral elements were selected for their compatibility

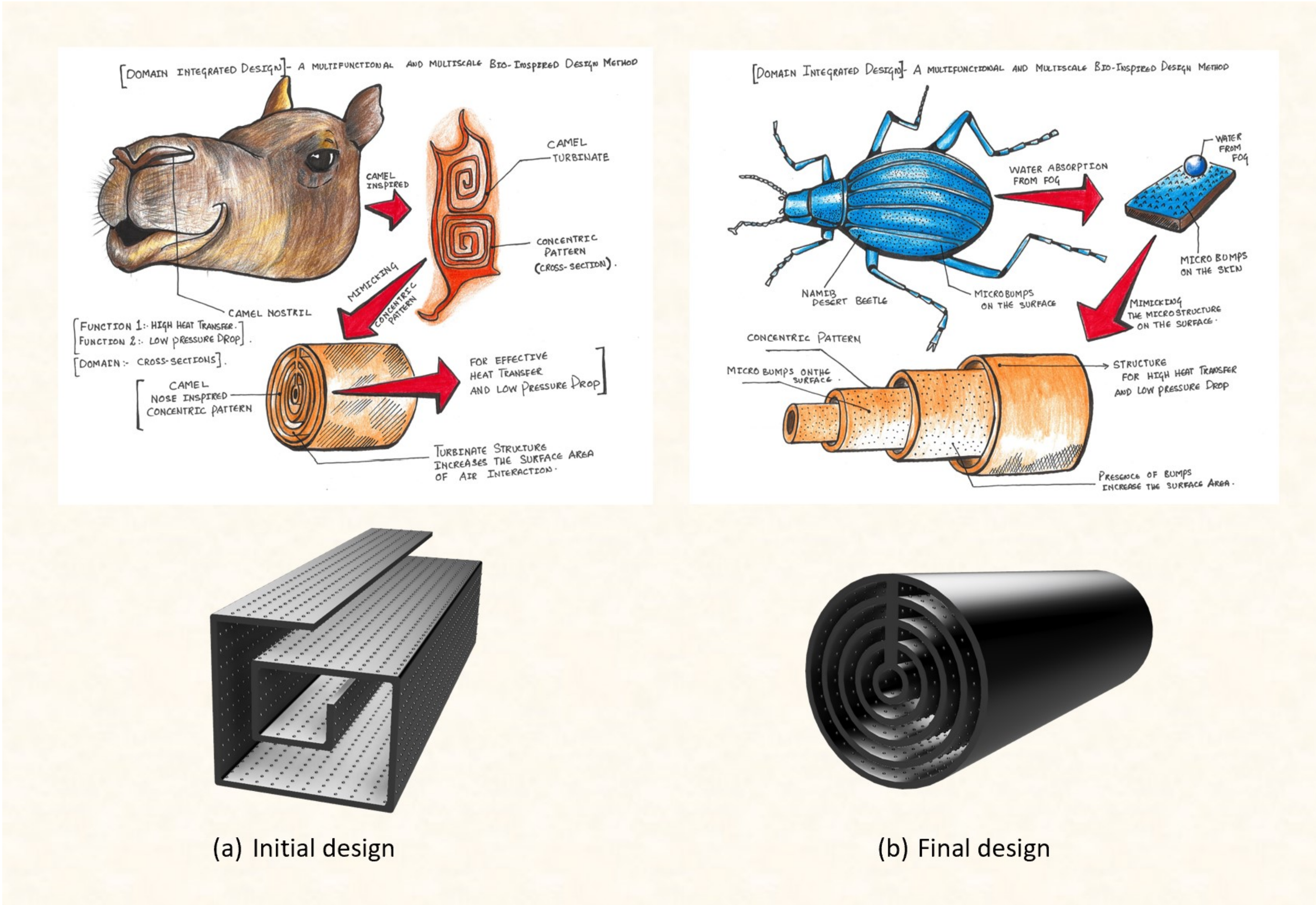


Figure 7.28: CAD models of the bio-inspired structures inspired by camel turbinates and Namib desert beetle micro-bumps a) Depicts the initial design comprising the loop-like structure with the micro-bumps on the surface b) Depicts the final design where the loops are replaced by concentric circles with the micro-bumps on the surface

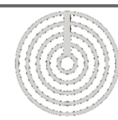
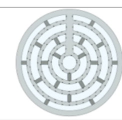
Design	Cross-sections
Turbinate + bumps (TB)	
Turbinate + dents (TD)	
Turbinate + bumps + internal projections (TBP)	
Turbinate + dents + internal projections (TDP)	

Figure 7.29: CAD models of the bio-inspired structures with a variety of cross-sections

with finite element analysis (FEA) simulation software [241]. Figure 7.30 displays the conceptual sketch of the simulation environment of the bio-inspired structures. Figure 7.31 displays the comparison chart of the bio-inspired structures to the conventional lattice structures for effective heat transfer and low-pressure drop applications. From the comparative chart, it is evident that the biologically inspired structures are significant in achieving low-pressure drop, and are comparable to the other lattice structures in achieving effective heat transfer. However, iterations are required for the bio-inspired designs to achieve a significant improvement in the effective heat transfer. The Mesh generation involves defining three regions with varying mesh densities: two regions with a coarse mesh excluding the lattice structure seat and one with a fine mesh incorporating the lattice structure seat to reduce computation time. The K-ω shear stress transport model is employed for simulation [242, 243]. Additionally, all designs undergo simulation at three different Reynolds numbers: 292,000 (Highly Turbulent Flow), 30,000 (Turbulent Flow), and 1,800 (Laminar Flow). From the results, it's apparent that the bio-inspired design has successfully addressed one function, namely low-pressure drop, outperforming other lattice structures. However, the second function, effective heat transfer, is not achieved because of the following

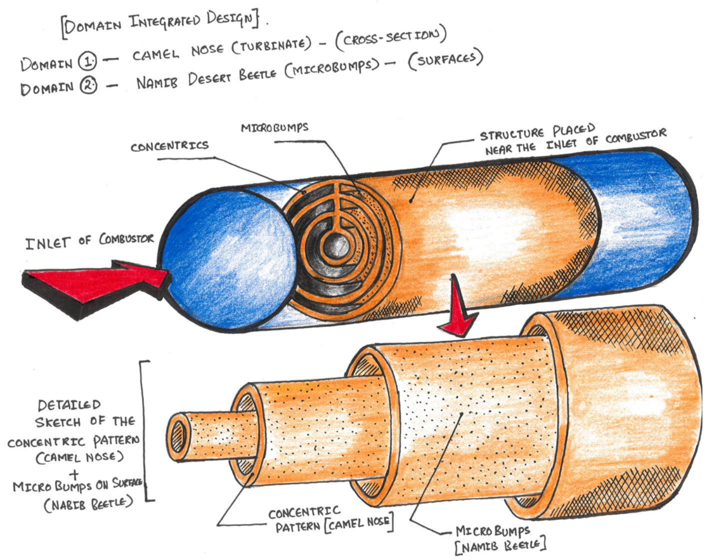


Figure 7.30: Simulation environment of the bio-inspired structures

- The turbinates contain mucus membranes that contribute to achieving more effective heat transfer, leveraging the energy released during moisture evaporation. However, in this study, the evaporative behavior was not considered relevant for the gas turbine application.

- Camel turbinates are typically mesoscale structures. For the current application, other desert organisms utilizing microscale structures may offer a more effective solution.

The proposed DID method addresses this challenge by employing meta-level design parameters for selecting the correct analogy. However, for future work, the current design will be modified to enhance air interactions with the structures without compromising on the low-pressure drop.

7.4 Summary

The validation of the systematic bio-inspired design process involves two processes:

- To search if the method reproduces an existing biomimetic product through a literature survey.

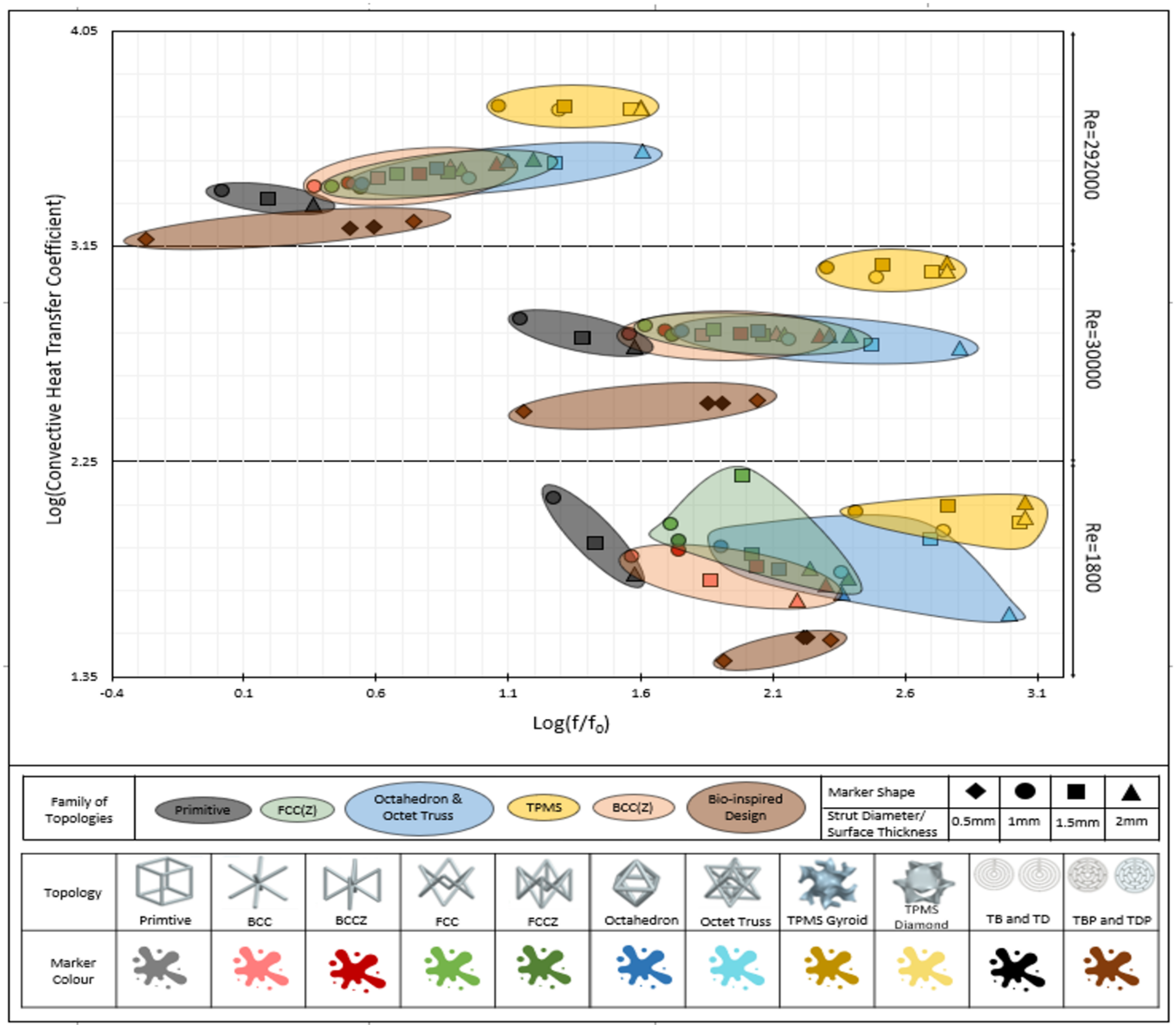


Figure 7.31: Comparison chart of the bio-inspired structures to the conventional lattice structures for effective heat transfer and low-pressure drop application

- To see if there are any closely related development versions of concepts developed using the method in the literature

The newly developed idea generation system is validated by creating three innovative bio-inspired multifunctional design concepts along with their initial embodiment models and comparing the performance of the generated designs with existing designs through simulations. The painless bio-inspired sutures, the efficient heat transfer, and low-pressure drop designs serve as validation for the method. Additionally, the bio-inspired multifunctional non-pneumatic tire design validates the meta-level design parameters.

Part VI

Summary and Future work

8

Summary and Future Work

This research has yielded a comprehensive idea-generation system that involves:

1. **Abstraction**: A novel abstraction technique has been developed, streamlining the complex system-level abstraction of biological features. This method introduces an embodiment-level abstraction of biological features, describing the function as a combination of integrated structure (across multiple scales) and the structural strategy (configurational arrangement).

2. **BIKAS (knowledge base)** : A manually curated database comprising more than 50 biological systems, organized based on their function, integrated structure across multiple scales, and structural strategy in terms of their configuration

3. **Domain Integrated Design (DID) method**: A novel classification and mapping technique that categorizes biological features based on their characteristic features, aligning them with specific geometric designations known as Domains. The selection and integration of these features from these Domains, considering both function and geometry, give rise to the creation of distinctive multifunctional and multi-scale

designs. Furthermore, this technique maps biological features back to their originating tissues, initiating a search for materials that exhibit properties compatible with these tissues

4. **Meta-level design parameters**: A novel quantitative criteria have been established to select appropriate biological features that share geometric relevance, scale, and exhibit similar functionalities.

5. **Expandable Domain Integrated Design (xDID) model**: The extension of the DID method expands the intricate categorization of complex biological features beyond the currently defined Domains. This extension encompasses the entire system model, incorporating the utilization of BIKAS, the DID Method, and meta-level design parameters.

6. **Validation**: The validation of the method and the system involved in the generation and simulation of novel multifunctional bio-inspired conceptual and early-stage embodiment models.

Figure 8.1 depicts several components that comprises the MBID idea generation system:

- Abstraction (Representation) of Biological Features: This involves the representation of biological features using a novel abstraction technique.

- Classification and Mapping of Biological Features: A method is employed to classify these features and map them to geometric designations (Domains) as well as their respective tissues.

- Meta-level Parameters: Incorporation of meta-level parameters to enhance the overall understanding and manipulation of the biological features.

- Quantitative Selection Criteria: Establishment of quantitative criteria to effectively select relevant biological features based on geometric relevance, scale, and functional similarity.

- Integrated Model: Creation of a model that seamlessly integrates all system components, including BIKAS, the DID Method, and meta-level design parameters.

- Digitization of Database: The final step involves the digitization of the generated database, facilitating easy access and utilization of the compiled biological feature information.

The idea generation system's validation involves generating and simulating novel multifunctional bio-inspired conceptual and early-stage embodiment models. Figure 8.2 depicts the entire process of the systemic multifunctional bio-inspired design.

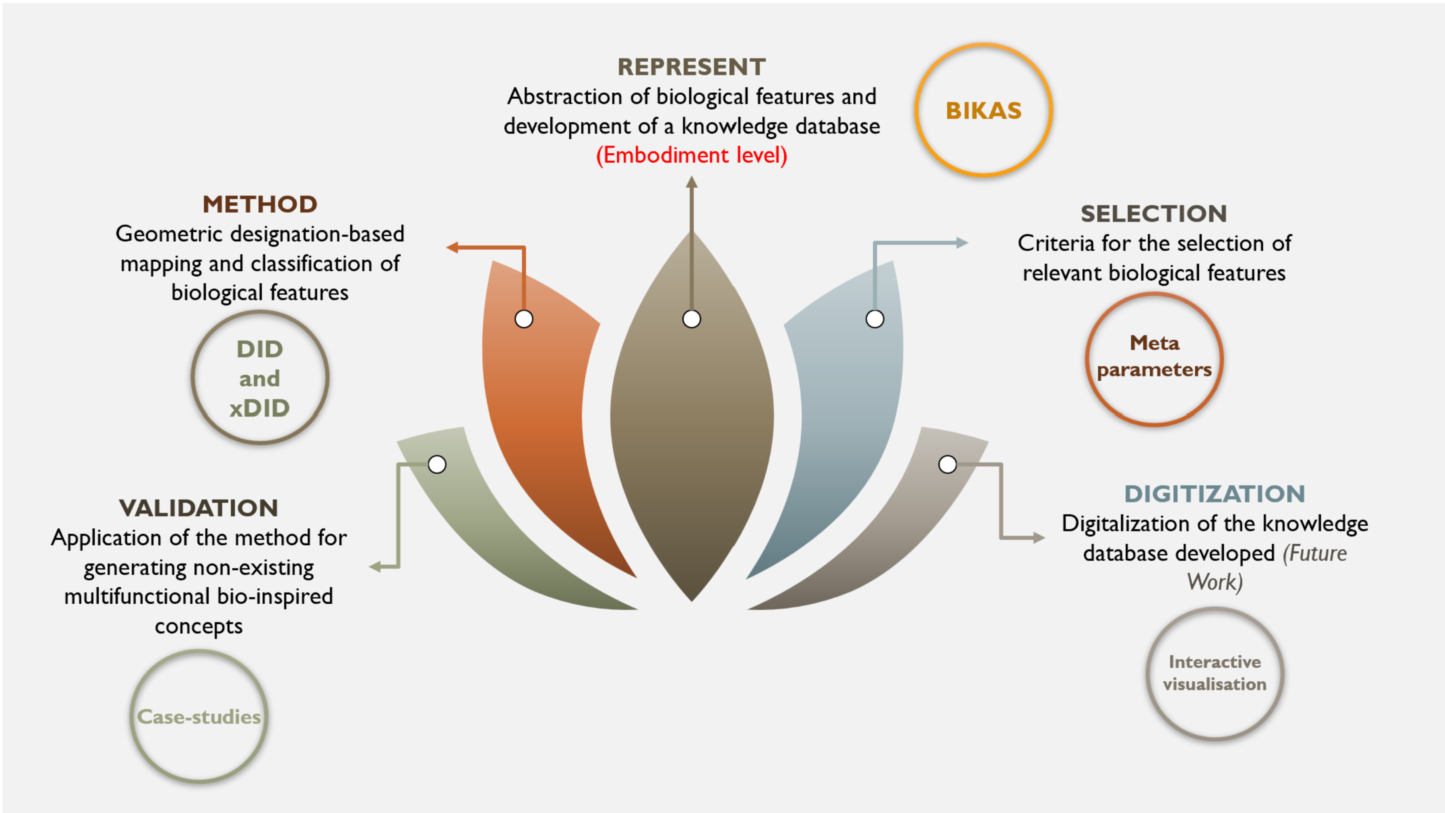


Figure 8.1: Multifunctional Bio-inspired Design system components: Representation, Method, Selection, Validation and Digitization

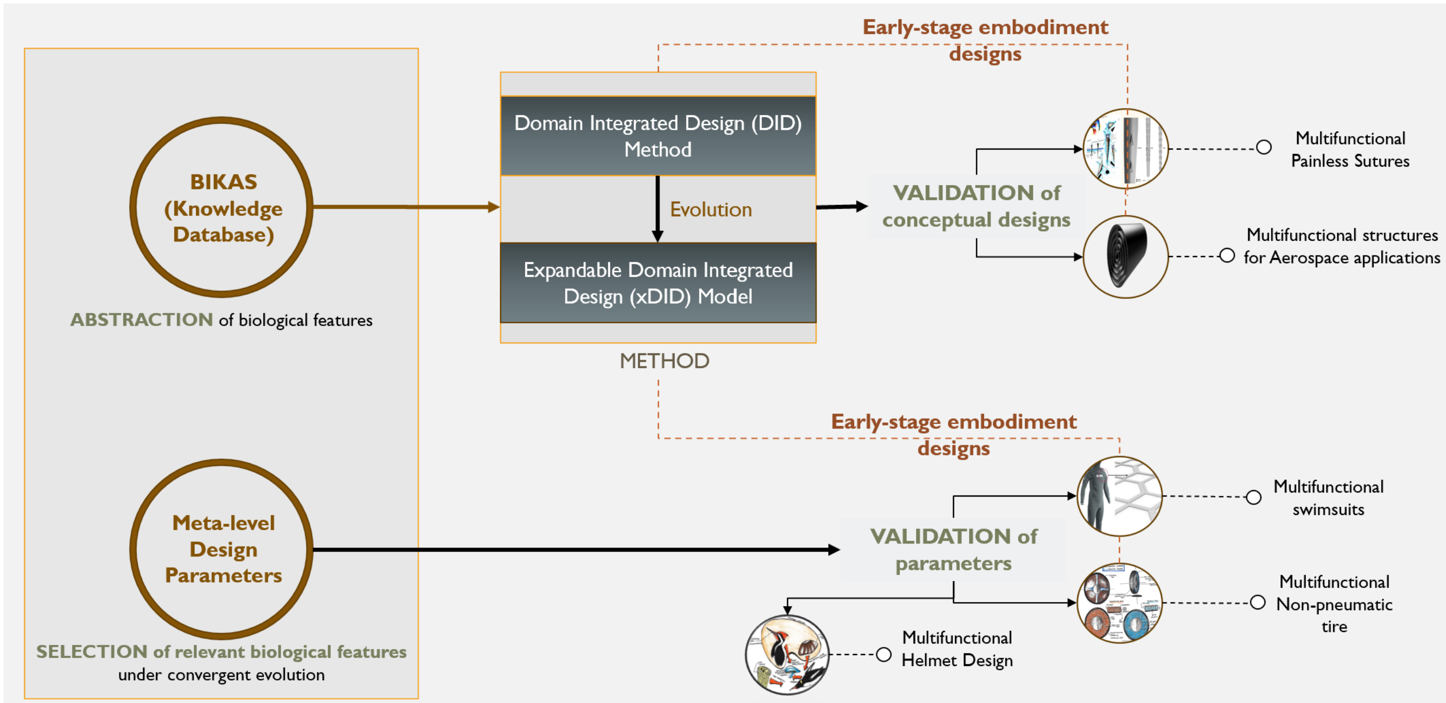


Figure 8.2: Validation of the system through the generation of multifunctional design concepts and early-stage embodiment models.

Future Work

Existing tools supporting the Bio-Inspired Design (BID) processes primarily focus on extracting biological information using functional keywords from academic articles, patents, and various data sources. Moreover, machine learning and artificial intelligence-based data extraction techniques employ semantic network graphs for idea generation. However, these techniques do not explicitly ensure the generation of multifunctional concepts. The ideation system presented in this research provides a comprehensive approach, incorporating a granular level abstraction technique. This technique includes the generation of a knowledge database comprising 50 biological features, as well as the DID and xDID methods, enabling the combination of multiscale geometries for generating multifunctional designs. Additionally, meta-level design parameters facilitate the selection between different geometries that serve the same function. The resulting knowledge database will serve as a crucial data source for any machine learning algorithm for the extraction and automatic classification of biological features into their respective geometric designations. Future work will focus on making the database available online and facilitating its expansion by allowing users to contribute biological features. The development of BIKAS, a new mapping and classification knowledge database, initially demands manual effort to associate biological features with their functions, integrated structures, and structural strategies. BIKAS aims to become the foundational structured dataset for generating an ontological Knowledge Graph and exploration and application of AI techniques for enhancement.

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