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A Comparative Analysis of the State-of-the-Art Methods for Multifunctional Bio-Inspired Design and an Introduction to Domain Integrated Design (DID)

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Abstract: Nature is a continuous source of inspiration for scientists and engineers for creating innovative products. In the past decade, many methods, frameworks, and tools have been developed to support the design and development of biologically inspired products. This research provides an overview of the current state-of-the-art bio-inspired design methods and identifies that there is a need for the development of methods to support multifunctionality in design. Although there are several methods that assist in the development of multifunctional designs inspired by biology, there is still a gap identified in the emulation and integration of biological features to achieve multifunctional bio-inspired designs. This paper presents a comparative analysis of the current methods for multifunctional bio-inspired design based on nine specific criteria and, in the end, introduces a new design method called Domain Integrated Design (DID) that will further aid in the generation of multifunctional design concepts inspired from biology.

Keywords: domain integrated design (DID); multifunctional bio-inspired design methods; bio-inspired innovation; conceptual design; transdisciplinary innovation

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1. Bio-Inspiration in Engineering Design

Up to 3.8 billion years of evolution have been a continuous source of inspiration for many engineers and scientists for solving complex engineering problems. Over the past two decades, there has been significant progress in developing frameworks, methods and tools that will assist engineers and designers in emulating nature's principles for the design and development of innovative products. For example, lotus leaf-inspired structures for superhydrophobicity [1], shark skin-inspired structures for fluidic drag reduction [2,3], replication of snakeskin structure for effective friction management [4], Namib desert beetle for water absorption [5], structures for effective energy absorption [6], beetle forewing for high load-bearing [7], etc. The emulation of nature's principles and strategies led to the development of many terms and definitions for bio-inspired design. A comprehensive study by Fayemi et al. [8] defines terms such as biomimetics, biomimicry/bio-mimesis, and bionics. In addition, the International Standards Organisation (ISO) 18458 provides similar definitions for biomimetics, biomimicry, and bionics [9]. However, bio-inspired design (BID), or biologically-inspired design, can be defined as an approach that uses analogies to biological systems to extract innovative solutions to solve difficult or complex engineering problems [10,11]. Apart from the definitions, Aziz [12] discussed the approaches of bio-inspired design, namely top-down (problem-driven) and bottom-up (solution-driven). The top-down approach starts from a problem definition, followed by identifying the relevant biological principles and strategies that solve the problem. On the other hand, a bottom-up approach starts with a biological discovery of principles and strategies, followed by identification of the problem where the biological discovery can be applied. In addition, Fayemi et al. [8] describes the levels of applying bioinspiration. Level 1 describes the mimicking of form, level 2 describes the mimicking of natural process and finally, level 3 describes the mimicking of the strategies of living.

To ease the emulation of nature-inspired strategies and principles, frameworks were designed that provide a sequence of steps which describe the process of emulation. Furthermore, methods were developed that describe the process of performing steps listed in a framework. In addition to frameworks and methods, tools were developed to assist the steps in a framework. This paper provides a comprehensive comparative analysis of the methods that assist in the multifunctional designs inspired from nature. Multifunctionality can be used in developing a wide variety of products as they reduce costs, enhance repairability and product lifetimes, and promote standardisation [13].

This paper is a review and exploration of the latest frameworks, multi-functional bio-inspired design methods, and the tools that assist the methods to achieve multi-functional bio-inspired innovative products. Furthermore, this paper evaluates the current multi-functional design methods according to nine specific criteria. The paper then introduces a method called Domain Integrated Design (DID) that is focused on classification of biological features or functional tissues (tissues that are responsible for achieving a function) into domains and exploration of function as a combination of structure and behaviour.

This paper is organised as follows. Section 2 discusses the bio-inspired design frameworks, methods, and tools. Section 3 discusses the design methods for multifunctional BID. Section 4 presents a comparative analysis of the methods discussed in Section 3. Section 5 introduces the proposed Domain Integrated Design (DID) method, Section 6 provides the discussions and, finally, Section 7 presents the conclusions.

2. Bio-Inspired Design Frameworks, Methods, and Tools

Previous research on the BID process has different versions of the description of existing frameworks, methods, and tools. The descriptions were purely subjective and depended upon the type of evaluation performed on the BID process. The study by Fu et al. [14] described methods such as DANE [10], IDEAS-INSPIRE [15], multi-biological effects (MBE) [16] and UNO-BID [17] as knowledge representation methods that use textual representation. Ask Nature [18] and IDEAS-INSPIRE are represented as knowledge data structures. Moreover, the structure–behaviour–function (SBF) and SAPPhIRE (represents parts, state, organ, physical effects, input, physical phenomenon, and action) constructs (can be called a biological analogy abstraction) used in DANE and IDEAS-INSPIRE, respectively, are described as feature recognition techniques. Likewise, other research studies also categorised SBF, and SAPPhIRE constructs as biological abstraction/representation techniques [19,20]. In addition, techniques such as MBE, and function-basis also fall under the biological abstraction/representation techniques category [21]. Goel and Hancock [22] categorised frameworks and methods as information processing techniques. On the other hand, methods such as IDEAS-INSPIRE, and DANE are categorised as computational tools that have functionally indexed libraries. From an assessment conducted on the tools for BID [17], frameworks were categorised as biomimetic process models, and the analogical representation constructs, including SBF, SAPPHIRE, Four-box, and BioM, as abstraction tools. Moreover, approaches such as taxonomy, and TRIZ were categorised as transfer tools, and Ask Nature as an application tool.

However, for this paper, adapted from the work by Wanieck et al. [23], the Frameworks are defined as describing the process of emulation of a biological principle or strategy through a sequence of steps. Methods describe the procedure for executing the steps described in a framework, and Tools assist in performing the steps. The reported literature on frameworks, methods and tools are reviewed in the following sections sequentially.

The frameworks, methods, and tools are extracted based on a keyword search: multi-functional bio-inspired design; bio-inspired design methods; and from review articles of design methods for multi-functional bio-inspired design. This research describes the latest frameworks and methods that support multi-functional bio-inspired designs, and tools that assist the multi-functional bio-inspired design methods.

2.1. Frameworks for Bio-Inspired Design

Frameworks such as Alborg bio-inspired design, biomimicry design, Design Spiral, and bio-solution design follow a common sequence of steps starting from problem definition followed by problem abstraction, initiation of a search for the potential biological analogy, and then translating the biological analogy into a solution [24]. Lenau et al. [9], systematically analysed frameworks such as ISO model [9], Biomimicry Design Spiral [25], Georgia Tech model [11], Paris Tech model [8] and DTU Bio-cards [26] and identified that there is a similarity in the steps followed by each of the frameworks, with significant differences. Although each framework differs in the number of steps, each framework follows a similar sequence starting from problem definition to evaluaiton. Frameworks such as design spiral have a value addition of using taxonomy to arrange biological systems which would aid in the selection of the relevent biological analogy [25–27]. A unified bio-inspired design framework (UNO-BID) by Fayemi et al. [17] comprises an eight-step approach from problem definition to application. This eight-step unified framework represents a holistic and detailed sequence to perform a biomimitic process. Figure 1 shows the steps and sequence provided by different frameworks that represents the entire flow of a biomimetic process.

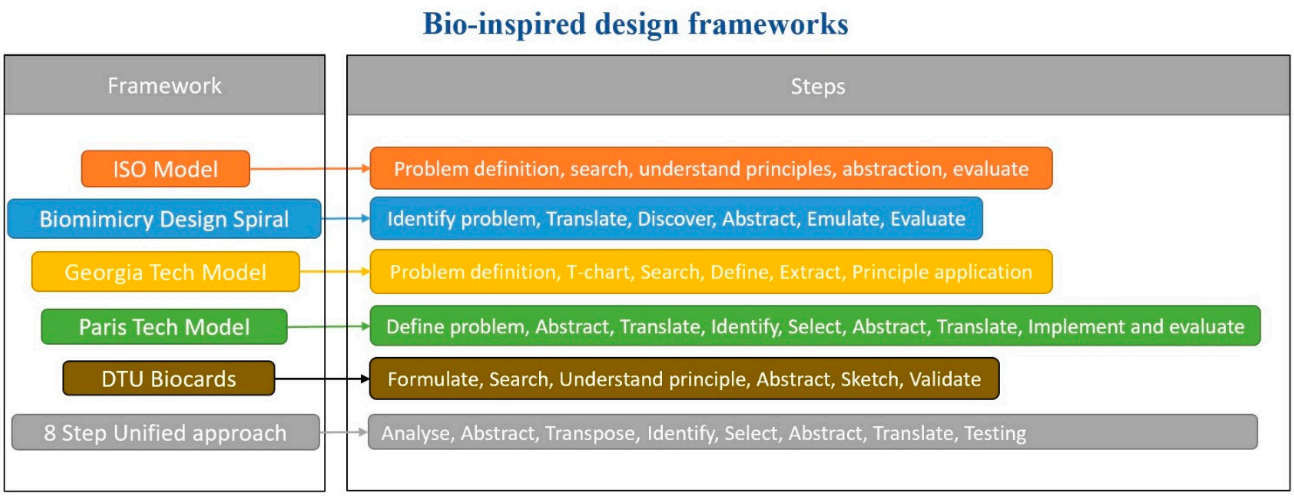

Figure 1. Frameworks for bio-inspired design, namely, ISO [9], Biomimicry Design Spiral [25], Georgia Tech model [11], Paris Tech model [8], DTU Biocards [26], and 8 Step Unified approach [17].

2.2. Methods for Bio-Inspired Design

In terms of methods for bio-inspired design, IDEAS-INSPIRE [15] is a software-based computational design system developed on the SAPPhIRE model, which focuses on the interaction between constructs, defined as parts, state, organ, physical effects, input, physical phenomenon, and action. The aim of IDEAS-INSPIRE is to develop novel solutions to design problems by forming a causal relation between biological systems and engineering systems. A designer analyses the natural and artificial systems to develop a novel solution for an engineering problem.

DANE (design by analogy to nature engine) [10] is a knowledge-based CAD (computer-aided design) system which follows the SBF approach to help designers find biological analogies, understand the functionality of the biological system, extract, abstract and apply the biological model to an engineering problem. Finally, DANE provides an ontology of structures, behaviour, and functions.

IDEAS-INSPIRE and DANE assist to perform the abstraction process of a biological analogy, by analysing the function exhibited by a biological entity. On the other hand, functional modelling is a method that uses a function structure diagram to extract the biological phenomenon or strategy aiding a designer to generate a biomimetic design concept [28]. Nagel [29] defines functional modelling as an abstraction of functional information of artifacts through design activities, for example, flow-based, SBF, etc., are functional modelling techniques. In the study carried out by Nagel et al. [30] on the functional models in aiding biomimetic conceptual design, they analysed the biological solution and an engineering solution with the same resemblance that assist the designers in developing BID concepts.

Nagel et al. [31] introduced analogy categories to represent or recognize and contextualize a biological system. The categories are divided into two types. The first type represents the physical characteristics such as form, surface, architecture, and material. The second type represents the non-physical characteristics such as function, material, and process. However, the analogy categories emphasise the exploration of the biological analogy and do not provide a detailed analysis of the biological systems. For example, the category "Form" represents the visual features such as shape, geometry, and aesthetics but do not provide the detailed analysis such as "what form?" and "what is that biological feature (or) underlying tissue that is responsible for achieving a certain function?"

2.3. Tools for Bio-Inspired Design

In terms of tools for bio-inspired design, ASK NATURE [18] is a functionally-indexed database of biological systems that follows a taxonomy of organising the biological information. It works by retrieving the biological analogy with a query performed by the user.

The Four-Box method [32], which evolved from a SR.BID (Structural BID) schema that follows SBF constructs, has been proposed for problem formulation for bio-inspired design. Four important conceptual categories are identified that represent the four boxes. The four important categories are: "function", that represents the actions a system must perform; "operational environment", that represents the location and conditions in which a system acts; "specifications", that represents material, shape, physical characteristics, etc.; and "performance criteria", that represents the degree to which a system performs its intended task. For analogy evaluation, a T-chart is proposed where the retrieved biological analogy is evaluated using the four identified categories.

A task-model tool [33] analyses the macrostructure of behaviour in biologically-inspired design by conducting a task analysis. From the principle of functional decomposition, this method decomposes a task into sub-tasks. The method incorporates compound analogy [34], problem-driven and solution-driven approaches for providing solutions. The method evaluates the solution obtained by the problem-driven and solution-driven approaches. If the solution address only one part of the problem, a new sub-task is created and the solution for the new sub-tasks are retrieved. The final solution would be the combination of solutions obtained from the sub-tasks.

An engineering-to-biology thesaurus [29] facilitates the designers to search for analogies using the terms that were developed based on the well-known function-basis lexicon. A functional basis lexicon is a combination of a verb–noun pair or a function–flow pair. A function represents a verb that is an action or a transformation, and flow represents a noun that is a material, energy, or a signal. There are eight classes of functions and three classes of flows [35]. The corresponding synonyms of these function and flow terms are replaced by biological terms using verbs and nouns.

A bio-inspired concept generation tool [36] was developed by integrating the function-based design methods and works on the framework of identifying, translating, repeating, and conceptualizing. The core of this tool is the functional modelling technique by using the functional-basis lexicon to decompose a problem statement into function, structure, behaviour, or a strategy. MEMIC (automated morphological matrix search tool) software is used to process the query and search for the relevant analogies.

SEABIRD-Scalable is a tool that supports the search for systematic biologically-inspired design [37]. This is a systematic tool to support the connection between the products listed in patents to the biological species and their strategies that are systematically described in the corpus. The term bio-transferability is introduced to classify, rank, and sort biological analogies using SMAA (stochastic multi-criteria acceptability analysis) techniques [38].

However, this technique uses descriptive measures to provide a decision support. Moreover, these techniques require extensive training and understanding of the criteria and sometimes might result in a trivial analysis.

Design heuristics are technique-based approaches that are used for product ideation processes. These techniques utilize a knowledge-based approach acquired through long experience. However, employing design heuristics for real-world application requires an in-depth information about material properties and usage [39].

BioM is an innovative database introduced by Jacobs et al. [40], in which over 380 cases were identified and studied from the literature, labelled as "biomimetics". The research concludes that a breakdown of biological principles is necessary to understand what types of biological form, process or interaction are responsible for a particular function.

Most of the bio-inspired design frameworks and information processing tools are domain-independent, meaning that they do not consider the biological processes that occur under the biological domain. For example, the functioning of a human eye depends upon the interactions and relations between many parts and the current design frameworks and tools consider only the function and do not consider the biological processes [22]. However, the key challenges for a BID are the problem definition/formulation, identification, and abstraction of relevant biological analogies. Most of the methods developed so far only assist in emulating a single function at a time [41]. On the other hand, most of the tools developed for BID assist only in the problem definition/formulation and search for relevant biological analogies. For example, latest tools developed using machine learning would assist in extraction of relevant biological analogies from patent databases and academic articles. Moreover, the machine learning algorithms perform classification and identification techniques to find similarities between biological and technological terms.

3. Methods for Multifunctional Bio-Inspired Design

Although a multitude of BID methods exist today, most of them assist in emulating only one functional feature. Very few of the BID methods addresses the emulation of multiple functions. This section discusses the principles and mechanism of the methods for multifunctional bio-inspired design.

BioTRIZ [42] is developed based on TRIZ techniques. BioTRIZ is a representation of a 6×6 matrix representing the parameters that need to be improved and some parameters that cause a contradiction. The parameters are substance, structure, time, space, energy, field, and information adaptation [9]. The BioTRIZ method may not explicitly define an approach to develop multifunctional structures but it allows the problem definition phase to support multifunctionality in BID [40]. This method provides a way to perform the problem definition and search for the relevant biological analogy steps in a framework.

A product-architecture-based tool, that relies upon a function-sharing approach for multifunctional BID, was introduced by Bhasin et al. [19]. The key feature of this method is to abstract biological analogies/adaptations by using function-sharing and to represent the interactions within the biological analogies/adaptations using hybrid product architecture tools such as reduced function–means tree. The reduced function–means tree utilizes three constructs and four interactions between the constructs to abstract a biological analogy. The three constructs are, namely, structure, behaviour, and function and the four interactions are, namely, (a) is solved by, (b) requires function, (c) physically realised by, and (d) interacts with. The function-sharing approach refer to a single biological feature solving multiple functions. For example, shark skin performs both anti-biofouling and drag-reducing functions simultaneously. The idea of this product-architecture-based method is to abstract biological analogies/adaptations by using a reduced function–means tree and then to combine the selected analogies to obtain the required features to design a product. The selection of those analogies is based on a specific criterion that relies upon utilization of behaviours and structures of already existing functions.

BioGEN is proposed by Badarnah and Kadri [43], and facilitates biological representation, principal identification, abstraction, and systematic selection. The method starts with the extraction of biological analogies that perform the required function. These extracted analogies are named as "pinnacles". The next step is to analyse and elaborate on the biological analogies' strategies and principles. This often leads to the problem of convergent evolution where more than one biological analogy can solve multiple problems. To reduce such complexity, the "pinnacles" are analysed under certain categories to extract the dominant feature among the "pinnacles". These categories are (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 dominant feature extracted is named the "imaginary pinnacle". It is also possible that there can be multiple imaginary pinnacles. In such cases, the selection is performed by using the design-path matrix. Finally, the selected strategies are combined to generate a design concept.

Trimming design method is another method derived from TRIZ techniques that uses existing resources after removing harmful components for an improved product. Furthermore, this method incorporates replacing certain system components that are inspired from biological strategies/adaptations. The whole process follows three-steps, namely, (a) functional analysis of the system to find out inefficient/harmful components by cause-effect–chain analysis (CECA), (b) searching and identifying the trimmed functions within the biological (MBE) database [16] and choosing the best possible solution by using the fuzzy comprehensive evaluation method, (c) transferring the biological solution into the system for better performance. The fuzzy comprehensive evaluation method evaluates three factors, namely compatibility, completeness, and flexibility [20].

Multi-bionics is another approach to produce better functional bionics through biological coupling mechanism [16,44]. Similarly, the multi-biological effects (MBE) method works on the integration of the idea of biological coupling and TRIZ techniques to achieve multiple functions. The method includes a diagrammatic model that represents biological elements, a data structure that provides a large source of biological inspiration and enables an integration with other innovative design methods [16]. Biological coupling is based on the idea that biological functionality is achieved as a combination (or) of coupling and interactions of various factors. These factors include morphologies, structures, materials, and constitutions of an organism. For example, the function of superhydrophobicity and self-cleaning of the lotus leaf is by a combination of non-smooth morphology, micro-nano composite structure and waxy materials [44].

The model of the function–means tree [45] is used to visualise multifunctional organs or means on the function–means tree that would support the designers in deciding what functions to merge and then initiate the search to find the relevant biological analogy that achieves the merged functions. The method uses the classification of functions into energy delivery functions, regulating functions, support functions, and auxiliary functions. The classified functions are then combined according to the requirements. Then, a search for a relevant biological analogy that solves the functions is initiated. The source of inspiration for this method is derived from a single organism solving multiple problems. The function term represents the desired output, and the means term represents the organ or component through which the function is realised.

The compound analogical design method [34] works on the principle of decomposing a problem statement into smaller sub-problems, followed by searching for relevant biological analogies/strategies that solve those sub-problems. The final solution is obtained by merging the solutions of all sub-problems.

The system-of-systems BID method [41] is about grouping different biological species based on their functionality and extracting a biological champion species from each of those groups and combining them to develop a multifunctional reconfigurable robot. For example, species that exhibit a desired biological functionality are grouped as biological list 1, the species that exhibit another desired functionality are grouped as list 2, etc. A champion species is selected from each list based on Pugh analysis. Finally, the derived features of the champion species are combined to design and develop multifunctional robots.

In a systematic literature review by N. Svendsen and T. A. Lenau [46] reported multi-functional design methods such as compound analogical design [34], BioTRIZ [42], and Wolff, 2017 [47] as current available methods that assist in multi-functionality. However, Wolff, 2017 [47] and compound analogical design [34] originate from the same principle of problem decomposition. Moreover, the systematic review by N. Svendsen and T. A. Lenau [46] recommends the future scope of BID is to translate the problem statement from a problem-driven BID approach to a solution-driven BID approach, as the solution-driven BID approach would support the development of multifunctional systems.

For the methods that search for a single organism that exhibits multiple functions, it is possible that those functions can be represented as a single function. For example, a nacre-inspired abalone armour that can resist bullets and knife strikes can be represented as a single function as "stop-solid" or "impact-resistant". However, it is argued that resisting bullets and knife strikes have different design requirements that generate different design constraints, thus they should be considered as two different functions [11]. For example, knife proof vests and jackets might have the design requirement of being lightweight and easy to wear and have a constraint of not exceeding a particular thickness and manufactured under certain costs. Similarly, bulletproof glasses or bulletproof defense systems have a different design requirement such as to withstand high velocity impact, have high energy absorption and have a constraint of not exceeding a particular weight and dimension. The next section provides the comparative analysis of the design methods for multifunctional BID.

4. Comparative Analysis of Multifunctional Bio-Inspired Design Methods

Reported comparative analysis on multifunctional BID analysed the methods and tools based on various criteria which were selected based upon their respective research and on the requirements of their end goal. This section first summarizes the criteria and the comparative analysis carried out previously on the multifunctional BID methods. Then, the newly chosen criteria and comparative analysis are presented.

The very first works on comparative analysis by Fu et al. [14], analysed bio-inspired tools based on the cognitive and implementation factors. The cognitive factors are (a) design fixation, (b) incubation, (c) modality of representation, (d) commonness, (e) distance between the source and target, (f) memory, (g) expertise, and (h) analogical reasoning process. The factors that are responsible for the implementation are, namely, (a) accessibility, (b) automation/computational synthesis, (c) solution-based approach, (d) problem-based approach and (e) education.

In a comprehensive comparative analysis, about forty-three tools for BID were analysed based on various factors. These factors are, namely, (a) class: analysis tools, abstraction tools, application tools and transfer tools, (b) type: DSC, taxonomy, thesaurus, ontologies, algorithm, and method (c) facilitate steps in biomimetic process, (d) approach, (e) accessibility, (f) availability, (g) field of knowledge, (h) dimension, (i) sustainability, (j) proof-of-concept [23].

Five problem-driven multifunctional bio-inspired design generation methods such as function-based design, compound analogical design, C-K theory, BioGEN, and BioTRIZ were analysed based on five different comparative criteria. The criteria are, namely, (a) type of engineering problem: number of objectives that a design must satisfy, (b) problem abstraction format: problem decomposition, trade-off, (c) type of interaction between strategies: transitive, causal or independent, (d) domain of integration: Technology or biological domain, and (e) type of solution generated: type of overall solution [48].

In this paper, the methods for multifunctional designs are analysed based on nine specific criteria, (a) source of inspiration: single organism or multiple organisms, (b) approach: problem-driven or solution-driven, (c) principles: functional decompositions, inventive principles (TRIZ)/trade-off, biological coupling, and functional sharing, (d) classification of features observed in a biological system, (e) criteria for selecting biological analogy, (f) feature parameters/factors for integration of analogies, (g) assistance in selection under convergent evolution, (h) simulation/testing of generated designs, and (i) dedicated database and IT-enabled tools.

Table 1 represents the comparative analysis performed on the design methods for multifunctionality. From the analysis, it is evident that most of the methods consider multiple biological organisms as a source of inspiration which explains that different/contrast functions are achieved with combination of multiple biological systems. As discussed in Section 3, only the reduced function–means (function sharing) and function–means methods have their source of inspiration from a single organism, which explains a single biological system solving multiple functions. Similarly, for the criteria on the approach, most of the methods have a problem-driven approach and only the reduced function–means method leads to a solution-driven approach. With the criteria on the principles, the majority of the methods follow function/problem decomposition, that is, to decompose a problem into various sub-problems and figure out solutions for different sub-problems. Only reduced function–means and function–means follow function-sharing, whereas the BioTRIZ method follows TRIZ techniques, and, finally, MBE and multi-bionics follow biological coupling principles.

For the classification of biological features criteria, only the function–means method categorises the features into energy delivery, regulation, support, and auxiliary functions. The rest of the methods do not have a classification for the biological features. For the criteria on the selection of biological analogy, reduced function–means utilises behaviours and structures of the already existing functions. System-of-systems BID uses Pugh analysis. BioGEN uses the design path matrix, and the trimming method uses fuzzy comprehensive evaluation. For the criteria on the parameters/factors for integrating different biological features to achieve multifunctionality, none of the methods discusses the parameters/factors for analogical integration. For the criteria on the assistance of selection under convergent evolution, that is, selection from many biological organisms solving the same function, only system-of-systems BID and BioGEN methods aid in the selection process. For the simulation and testing criteria, most of the methods end at the conceptual stage and do not validate their result. Only system-of-systems BID method is designed to design and develop reconfigurable robots. For the database and IT-enabled tools criteria, only BioTRIZ, MBE and trimming methods have their own respective web-based tools and databases, respectively. In addition to the analysis, none of the methods have addressed the integration of multiscale features that are responsible for the achieving a particular function.

From the detailed analysis of the current state-of-the art methods for multifunctional bio-inspired designs, the following gaps are found. Firstly, there is a need for a new approach for the classification of observed features in biological systems at an intricate/detailed biological level. The classification at detailed biological level will bring both biologists and engineers onto a common platform to emulate highly efficient biological strategies. Secondly, an expandable knowledge database for IT-enabled tools is needed to retrieve and visualize the biological systems. Thirdly, extraction of design factors is essential to aid designers for an enhanced understanding of biological strategies. For example, changing the orientation of certain biological features results in different functionalities. Finally, extraction of parameters is necessary to aid designers to select the relevant biological analogy.

To address the above gaps, a new design method called Domain Integrated Design (DID) is proposed in this paper. The next section discusses the notion of the proposed method in detail.

Table 1. Comparative analysis of the design methods for multifunctional bio-inspired design.

Method	Inspiration	Approach	Principles	Classification of Features in Biological Systems	Criteria for Selecting Biological Analogy	Feature Parameters/Factors for Integration of Analogies	Assistance in Selection under Convergent Evolution	Simulation and Testing of Generated Designs	Database and IT-Enabled Tools
Reduced function means (RF-M) [19]	Single organism	Lead to solution-driven	Function sharing	⚫	Behaviours and structures that use already existing functions	⚫	⚫	🔵	🟠
Compound analogy [34]	Multiple organism	Problem-driven	Function decomposition	⚫	🟠	⚫	⚫	🔵	⚫
BioTRIZ [42]	Multiple organism	Problem-driven	TRIZ Techniques	⚫	🟠	⚫	⚫	🔵	Web tool
System-of-systems BID [41]	Multiple organism	Problem-driven	Function decomposition	⚫	Pugh Analysis	⚫	yes	Prototype (Robotics application)	⚫
Multi-Bionics [16,44]	Multiple organism	Problem-driven	Biological coupling	⚫	🟠	⚫	🟠	🟠	🟠
Multi-Biological Effects (MBE) [16]	Multiple organism	Problem-driven	Biological Coupling	⚫	🟠	⚫	🟠	🟠	Multi Biological Effects (DB)
Function-Means [45]	Single organism	Problem-driven	Function decomposition & Function sharing	Energy delivery and regulation	🟠	⚫	⚫	🟠	⚫
BioGEN [43]	Multiple organism	Problem-driven	Function decomposition	⚫	Design path matrix	⚫	yes	🔵	⚫
Trimming method [20]	Multiple organism	Problem-driven	Function decomposition	⚫	Fuzzy comprehensive evaluation	⚫	⚫	🔵	Multi Biological Effects (DB)
Wolff [47]	Multiple organism	Problem driven	Function decomposition	⚫	🟠	⚫	🟠	🟠	🟠
Domain Integrated Design (DID)	Multiple organism	Problem driven	Function decomposition	Domains	yes	Meta-design factors and parameters	yes	yes	yes

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

5. Domain Integrated Design (DID)

DID is built on the notion of classifying the observed functional features in various biological systems into their geometrical designations. The domains are derived from geometric designation of biological features that are applied in many engineering applications. The function-performing tissues in various biological entities are identified and are mapped to their respective domains. Each domain encompasses different types of function performing tissues derived from plant and animal family. The classification of features particularly at tissue levels is based on the notion of the organisation of living systems where cells are described as the fundamental working unit of a living system, and a group of similar cells combine to form a tissue that performs a specific function [49,50]. Most of the observable functional features in a living system are either tissues or a combination of different tissues. Thus, the mechanism of the DID method is a classification and a mapping between the functional biological features (tissues) and their geometric designations.

The designers can combine different features from these domains to design and develop multiscale and multi-functional designs. Based on DID classification system, a knowledge database is built for the retrieval and visualization of biological features for ideation. Furthermore, meta-level design factors (can be described as feature-level attributes) are extracted to further enhance the design ideation. In addition, meta-level design parameters are proposed for the emulation and effective selection and combination of relevant biological analogies, thereby solving the problem of convergent evolution. Convergent evolution can be defined as different biological entities exhibiting the same functionality in radically different ways. Figure 2 is a graphical representation of the map between the observed functional features in both animal and plant family (tissues) to their corresponding geometric designations (domains). The domains are surfaces, cellular structures, cross-sections, and shapes. The cross-sections and shapes are described as sub-domains of cellular structures. This is because most of the observed cross-sections and shapes have cellular structure as an underlying framework. Nevertheless, this classification and mapping will act as the common platform for designers and biologists to emulate the biological strategies.

Figure 3 is a schematic of the encompassed tissues from plant and animal family arranged in their respective domains. In addition, each biological entity is abstracted by using Structure, Behaviour and Function construct. In the proposed DID method, function is defined as a combination of structure and behaviour. For example, the micro-level pointed projections (papillae) on a lotus leaf [1] represent the structure and the arrangement of the papillae in a random manner [51] represents the behaviour. The knowledge database is built on abstracting the biological entities by using the structure, function, and behaviour construct. Table 2 is a collection of biological systems categorised into Surface domain along with their function, structure, behaviour, and the tissue that is responsible for the functionality. Likewise, Tables 3–5 are the collection of biological systems categorised into cellular structures domain, shapes and cross-sections, respectively.

Table 2. Biological systems categorised into surface domain with their responsible functional tissues.

Biological System	Function	Structure	Behaviour	Tissue	Domain
Lotus leaf	Superhydrophobicity	Pointed microstructures with wax layer [1]	Random micro perturbances [51]	Epidermal tissue [52]	Surface
Borrowing pangolin	Anti-wear	Overlapping scales [53]	Outward scales [54]	Keratinous scales [55]	Surface
Shark skin	Drag reduction	Hierarchical microscale arrangement [2]	Flexibility [2]	Dermal denticles (Dentine) [56]	Surface

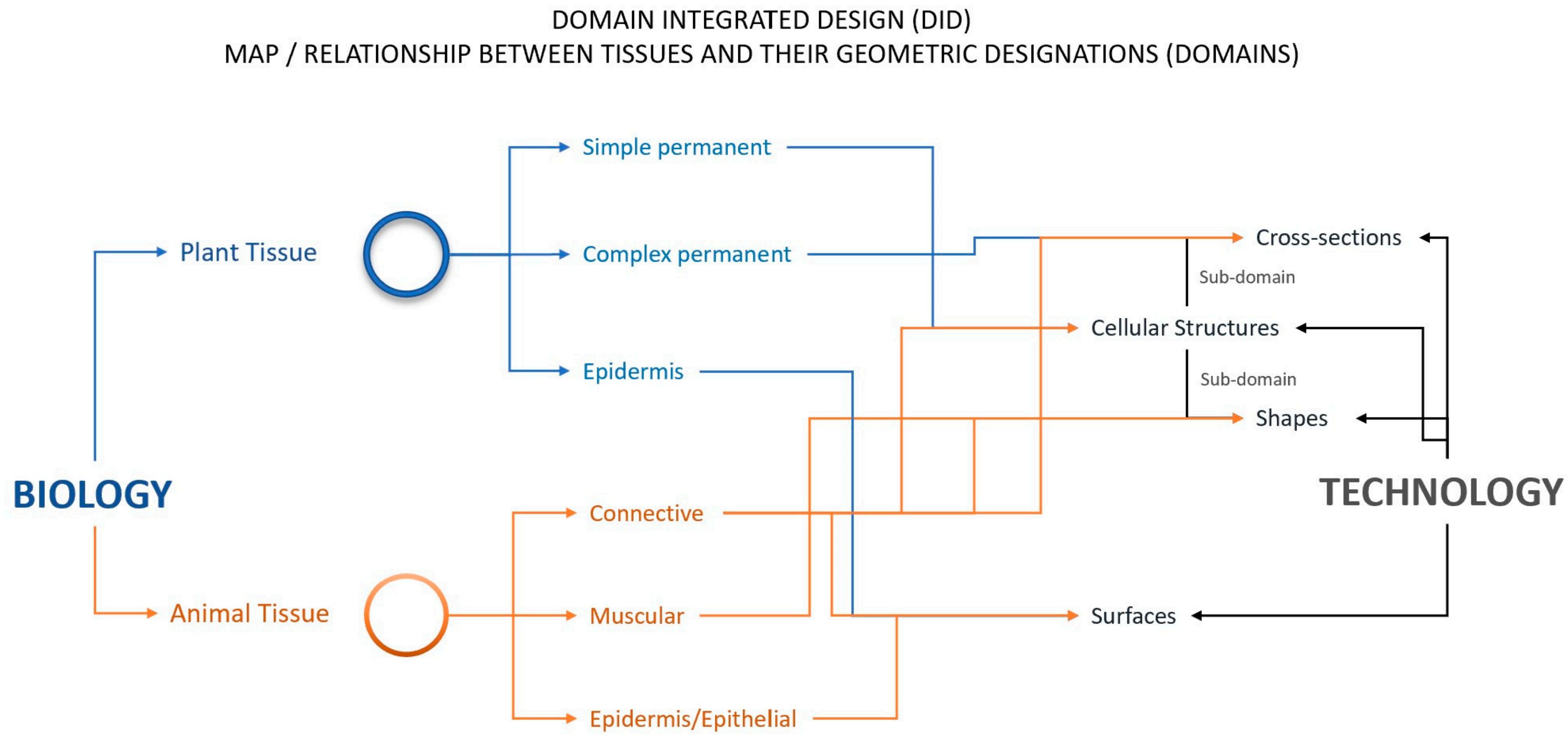

Figure 2. Domain Integrated Design (DID) framework that shows the mapping of tissues and their geometric designations. A relation between biology and technology (engineering).

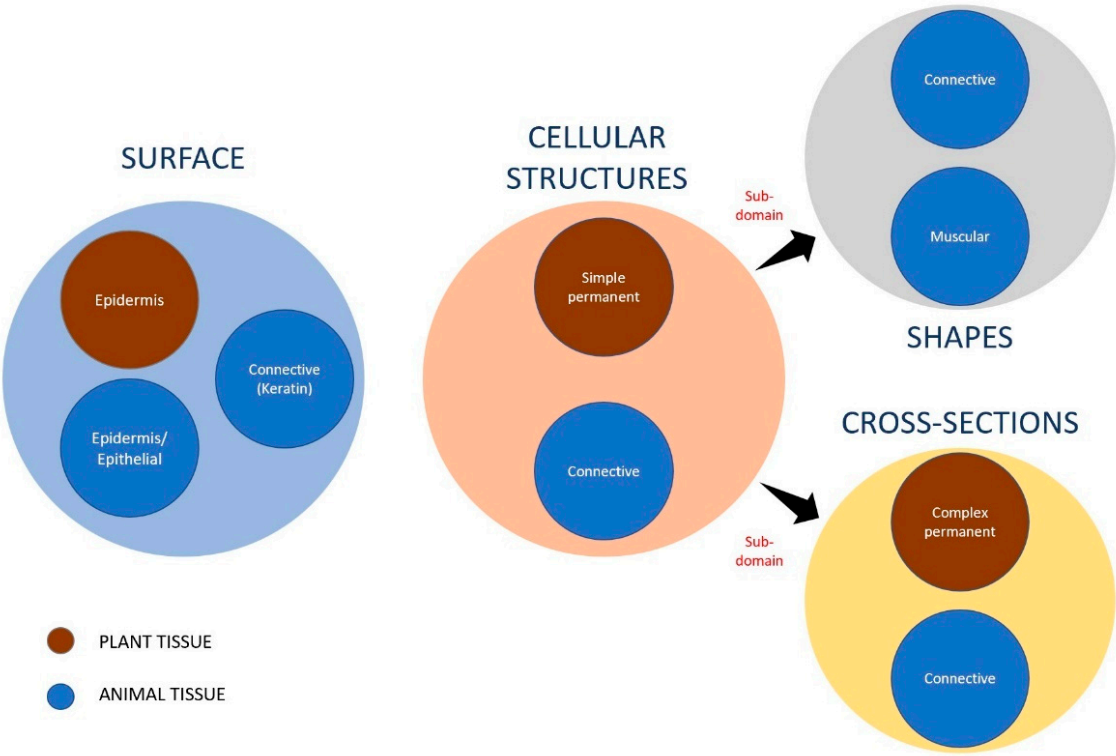

Figure 3. Shows the schematic of the arrangement of function performing tissues from plant and animal family into domains.

Table 3. Biological systems categorised into cellular structures domain with their respective functional tissues.

Biological System	Function	Structure	Behaviour	Tissue	Domain
Luffa sponge	Energy absorption and water absorption	Fibrous network structure [57]	The fibre grows in longitudinal direction [57]	Xylem and Phloem (Vascular bundles) [57]	Cellular structures
Iris Leaves	Stiffness	Sandwich panel separated by low density foam [58]	Stochastic Voronoi low density foam structure [58]	Sclerenchyma [59]	Cellular structures
Bird skull	Lightweight	Sandwich structure [58]	Trabeculae foam [58]	Trabeculae [60]	Cellular structures

Table 4. Biological systems categorised into shapes domain with their respective functional tissues.

Biological System	Function	Structure	Tissue	Domain
Penguin	Aerodynamic/Fluidic drag reduction	Spindle shape [61]	Body skeleton [61]	Shape
Boxfish	Aerodynamic/Fluidic drag reduction	Symmetrical box [62]	Carapace [63]	Shape
Diatom	Energy absorption	Transverse corrugated structure [64]	Siliceous cytoskeleton [65]	Shape

Table 5. Biological systems categorised into cross-section domain with their respective functional tissues.

Biological System	Function	Structure	Tissue	Domain
Kingfisher	Ability to cruise through different densities	Rotational parabolic cross-section [66]	Connective tissue [67]	Cross-section
Bamboo	Energy absorption	Multi-cell structure [6]	Vascular bundle [6]	Cross-section
Horsetail	Energy absorption	Hollow multi-cell structure [6]	Sclerenchyma [68]	Cross-section

To validate the proposed DID method, a painless suture-pin/leg is designed and analysed [69]. The newly designed suture-pin/leg reduces the pain in the patient by minimizing the skin rupture at the time of insertion. Inspired by the kingfisher's rotational parabolic cross-section to cruise from air to water without a splash, this unique structure reduces the amount of rupture on the skin at the time of insertion. Furthermore, to keep the suture rigid in its place and to avoid external disturbances, features inspired by porcupine quills are added to the suture-pin/leg. The sutures are biodegradable and do not require removal and thus reduce a patient's multiple visits to the hospital. In the case study, a kingfisher's beak is classed as the cross-sectional domain and porcupine quills are classed as a surface domain. Figure 4 shows the schematic of the designed suture pin/leg design.

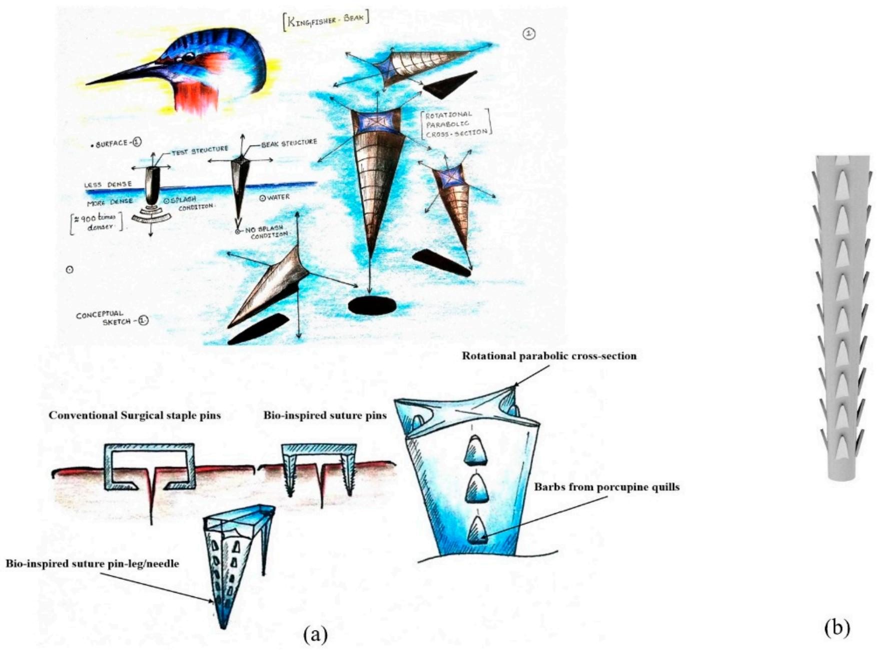

Figure 4. (**a**) Conceptual sketch of the painless suture. (**b**) Design of the bio-inspired painless suture pin/leg by implementing DID method [69].

Furthermore, the DID method facilitates the idea-generation of entirely new or innovative concepts, the validation of the DID method relies on the ideation effectiveness. The ideation effectiveness is measured by the variety metric score given by Shah et al. [70], Nelson et al. [71], and Linsey et al. [72], respectively. As bio-inspired design is mostly used for reducing material, energy and cost, the concepts generated from this method are validated according to a creative product (CP) score by measuring the novelty, usefulness, technical feasibility, and environmental impact, respectively [73]. Moreover, the generated concepts are simulated and validated by comparing with existing designs such as the domain specific performance validation reported by Seepersad et al. [74].

6. Discussions

Although the current state-of-the art methods for multifunctional bio-inspired designs offer designers a broad perspective in analysing the biological systems for emulation, the challenge often is the search for and identification of a relevant biological analogy, which requires a detailed abstraction of the features of a biological system. Even though tools are developed to extract biological knowledge from various sources of biological information, they lack in extracting the biological principle behind achieving a specific functionality. However, the newly proposed DID method is the next step to address the understanding of the biological principle by using the notion of SBF.

In contrast to the categories provided by Nagel et al. [31], firstly, the DID method classifies the biological features or functional tissues that are responsible for achieving a functionality into their respective geometric designations, called domains. Domains specify "which biological feature?", "which functional tissues?", and "which structure?". DID method then proposes function as a combination of structure and behaviour and introduces "meta-level design factors" that further enhance the understanding of the biological analogy. Figure 5 shows the contrast between analogy categories by Nagel et al. [31] and the DID method. The analogy categories emphasise the contextualisation of the biological system, whereas the DID method emphasises classification, followed by understanding of the biological system.

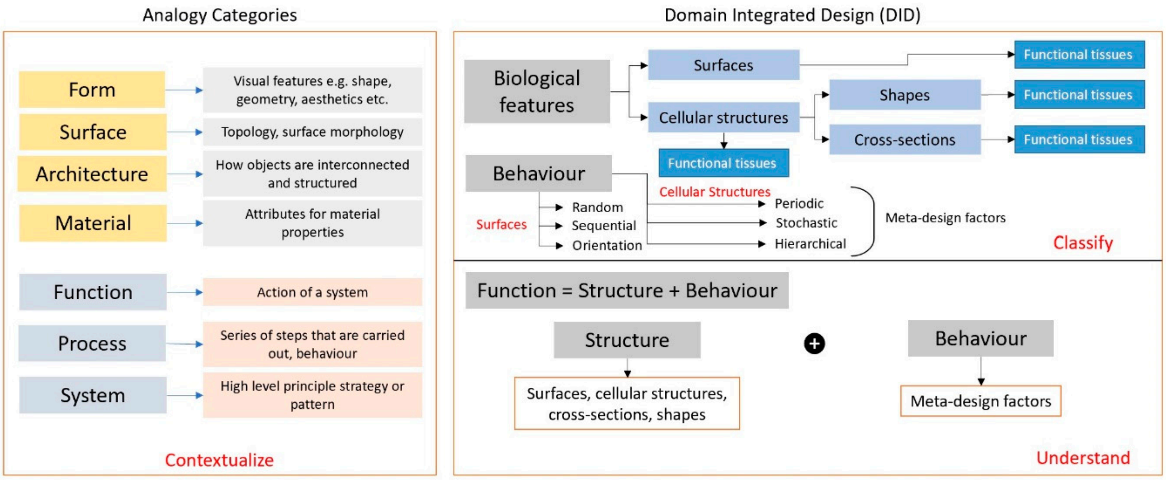

Figure 5. Schematic showing the analogy categories Nagel et al. [31] vs. DID method.

There is quite a distinction between the current state-of-the-art methods for multifunctional bio-inspired designs and DID. Firstly, a function-sharing principle using product architecture describes a single functional feature that can achieve multiple functions. For example, shark skin riblets exhibit drag reduction and anti-biofouling functions. Similarly, the lotus leaf exhibits superhydrophobicity and superoleophobicity. However, these functions (in the lotus leaf) can be described as a single function as "liquid-repulsion". It is argued that if the two functions have different requirements that result in different design constraints, they should be considered as two different functions. However, to achieve contrast and entirely different multi-functions, the proposed DID method would come in handy for the designers, for example, in lightweight and erosion-resistant structures. These two functions cannot be described as a single function. The DID method would further contribute to achieve an entirely new function.

Secondly, establishing a connection between biology and technology in terms of functional tissues and their geometric definitions to aid in interdisciplinary concept generation. Although tools such as the function basis lexicon, which uses grammar to corelate technological terms and biological terms, reduces the gap between technology and biology, this approach does not specify the biological features (tissues) that are responsible for exhibiting certain functions. The unique classification of functional tissues into domains enables further reduction of the gap and makes it easier for biologists, engineers, and designers to collaborate effectively.

P. Schachinger and H. L. Johannesson [75] describe functional coupling as a conflict that arises when choosing a design solution to fulfil one or more design requirement. It is interactions between incompatible parallel solutions causing negative influence. To address such an incompatible problem in choosing design solutions, the DID method relies on the convergent evolution process, where similar functions are exhibited by different organisms in radically different ways. In other words, to solve the same function, different alternatives with radically different structure and material can be found. This approach solves the incompatibility of the design solution. For example, a drag-reduction function can be solved by mimicking the surface of shark skin, or by using a penguin's spindle shape or by using a boxfish cross-section.

Finally, development of a dedicated knowledge database to establish the relation between natural and artificial systems by using various biological abstraction constructs such as SAPPhIRE, SBF, and taxonomy assist designers to emulate designs by enabling a clear understanding of biological analogy. However, these databases are mostly utilised for emulation of single function. The knowledge database of DID for ideation is built on the notion of classification of functional tissues into domains, SBF, and a ranking system based on the scale of application (micro, nano, etc.) would aid designers in effective combination and emulation of efficient multifunctional BID.

Figure 6 describes the schematic of the working of the current state-of-the-art methods and the potential fit of the proposed DID. This schematic provides a comparative chart of various methods with their origins (inspiration from single organism or multiple organisms), associated principles, classification of biological features, selection of biological features, validation and finally their database and information technology enabled applications. From this comparative chart, it is evident that only function–means method works on the integration of principles of function-sharing and problem/function decomposition. However, the function–means method initiates the search for single organism that exhibits multiple functions. Classification of biological features is carried out only by the function–means method, and the proposed DID.

The major strength of DID process is the classification of biological features (functional tissues) into various domains and, furthermore, such a classification would enable designers, biologists, and engineers to collaborate on a common platform to create innovative, highly efficient products. Compared to DID, none of the methods provide classification of functional tissues into their geometric designations (domains). Only methods such as systems-of-systems BID, and BioGEN assist the selection under convergent evolution. On the other hand, only reduced function means (RF-M), system-of-system BID, BioGEN, and trimming method provide criteria for the selection of relevant biological analogy. However, the generated concepts from most of the methods and do not procced for simulation-based validation. Figure 7 is a schematic representation of the strengths and weakness of the proposed DID method.

However, the DID method has some limitations regarding the classification and exploration of functions that are caused due to chemical secretions. For example, bioluminescence in fireflies [76,77], pheromones used in ants for communication and navigation [78,79]. The future directions of this research will be towards discovering ways to include the chemical functionality into the Domain Integrated Design (DID) method to enhance the ideation of advanced and innovative products.

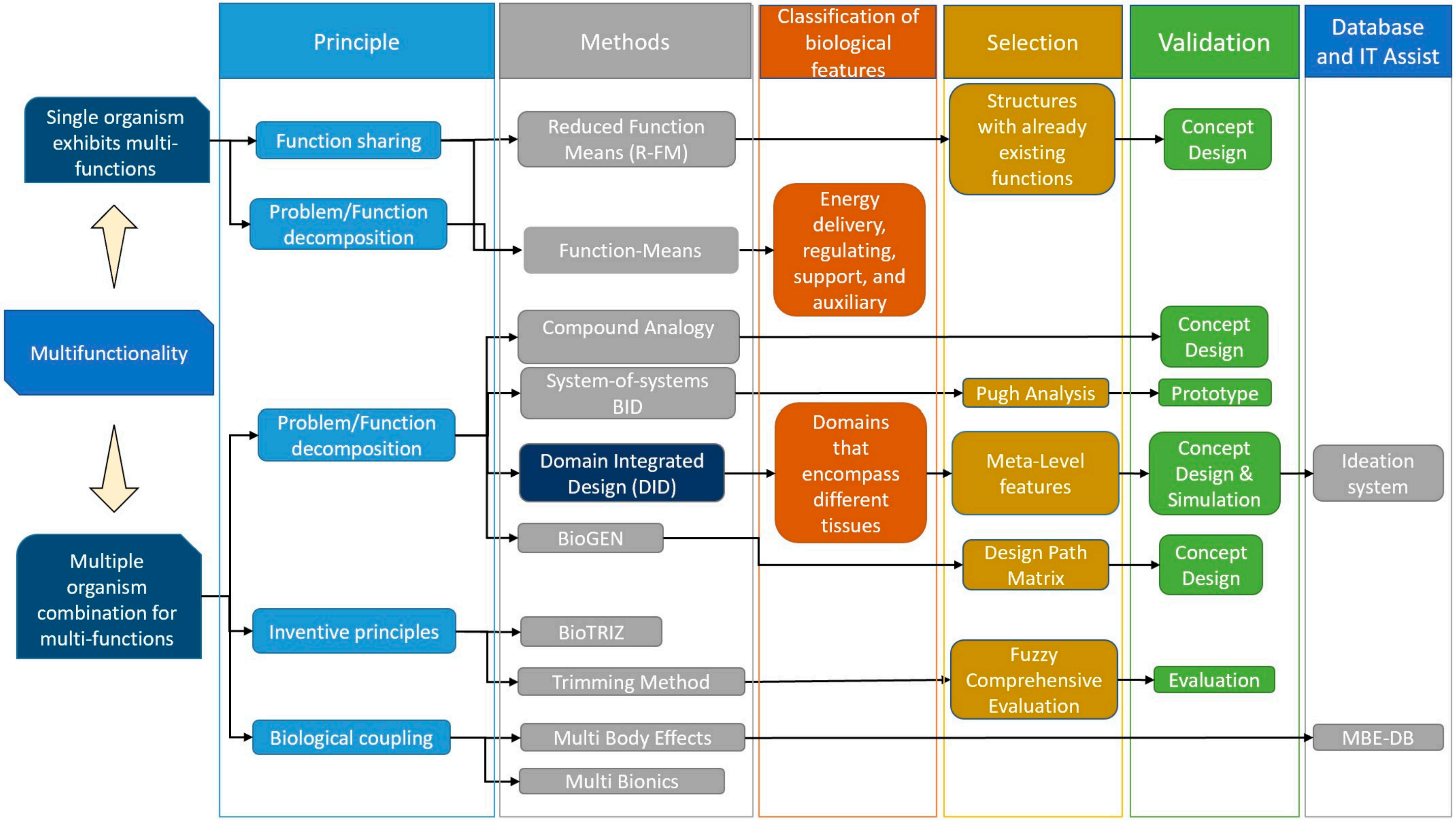

Figure 6. A graphical representation of the current state-of-the-art methods for multifunctional bio-inspired designs and Domain Integrated Design (DID). Methods are, namely, reduced function means [19], function–means [45], compound analogical design [34], system-of-systems BID [41], BioGEN [43], BioTRIZ [42], trimming method [20], multi body effects [44], multi bionics [16].

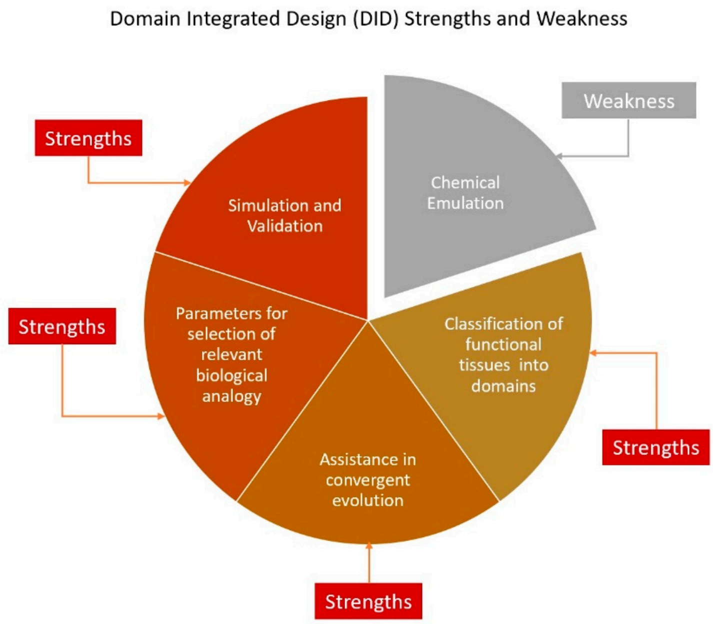

Figure 7. Strengths and weakness of DID.

7. Conclusions

The current state-of-the-art methods for multifunctional bio-inspired designs are analysed and a new multifunctional design method DID is proposed. This research presented an analysis of the current methods and provided an introduction of the DID method. Biological systems have been continuously evolving for 3.8 billion years and it is extremely tough to obtain data for each species. Moreover, in nature there is a notion of convergent evolution, where the same functionality is exhibited by different organisms in radically different ways. On the other hand, functionality is achieved by synergetic interactions of various aspects such as the structural aspect, and the behavioural aspect of the organism. Hence, it is necessary to consider the underlying factors while emulating the biological analogy.

BID is an interdisciplinary field, and it is essential to involve biologists, engineers, and designers in performing emulation of highly efficient, innovative, and sustainable biological analogies. DID is the next step in bridging the gap between biology and technology to bring the biologists, engineers, and designers onto a common platform.

The details and definitions of the proposed domains and the development and the expansion of the knowledge database with the abstraction of the function, structure, and behaviour exhibited by the biological entities with their respective meta-level design factors will be the future work of the research.

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References

1. Zhang, M.; Feng, S.; Wang, L.; Zheng, Y. Lotus effect in wetting and self-cleaning. *Biotribology* **2016**, *5*, 31–43. [CrossRef]
2. Luo, Y.; Yuan, L.; Li, J.; Wang, J. Boundary layer drag reduction research hypotheses derived from bio-inspired surface and recent advanced applications. *Micron* **2015**, *79*, 59–73. [CrossRef] [PubMed]
3. Zhang, D.; Li, Y.; Han, X.; Li, X.; Chen, H. High-precision bio-replication of synthetic drag reduction shark skin. *Chin. Sci. Bull.* **2011**, *56*, 938–944. [CrossRef]
4. Tiner, C.; Bapat, S.; Nath, S.D.; Atre, S.V.; Malshe, A. Exploring convergence of snake-skin-inspired texture designs and additive manufacturing for mechanical traction. *Procedia Manuf.* **2019**, *34*, 640–646. [CrossRef]
5. Brown, P.S.; Bhushan, B. Bioinspired materials for water supply and management: Water collection, water purification and separation of water from oil. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2016**, *374*, 20160135. [CrossRef]
6. San Ha, N.; Lu, G. A review of recent research on bio-inspired structures and materials for energy absorption applications. *Compos. Part B Eng.* **2020**, *181*, 107496.
7. Chen, J.; Tuo, W.; Guo, Z.; Yan, L. The 3D lightweight structural characteristics of the beetle forewing. *Mater. Sci. Eng. C* **2017**, *71*, 1347–1351. [CrossRef]
8. Fayemi, P.-E.; Maranzana, N.; Aoussat, A.; Bersano, G. Bio-inspired design characterisation and its links with problem solving tools. In Proceedings of the DS 77: Proceedings of the DESIGN 2014 13th International Design Conference, Dubrovnik, Croatia, 19–22 May 2014; pp. 173–182.
9. Lenau, T.A.; Metze, A.-L.; Hesselberg, T. Paradigms for biologically inspired design. In Proceedings of the Bioinspiration, Biomimetics, and Bioreplication VIII, Denver, CO, USA, 4–8 March 2018; p. 1059302.
10. Vattam, S.; Wiltgen, B.; Helms, M.; Goel, A.; Yen, J. Dane: Fostering Creativity in and through Biologically Inspired Design. In *Design Creativity 2010*; Springer: Berlin/Heidelberg, Germany, 2011.
11. Helms, M.; Vattam, S.S.; Goel, A.K. Biologically inspired design: Process and products. *Des. Stud.* **2009**, *30*, 606–622. [CrossRef]
12. Aziz, M.S. Biomimicry as an approach for bio-inspired structure with the aid of computation. *Alex. Eng. J.* **2016**, *55*, 707–714. [CrossRef]
13. Lenau, T.A.; Lakhtakia, A. Rationale for Biologically Inspired Design. In *Biologically Inspired Design*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 37–45.
14. Fu, K.; Moreno, D.; Yang, M.; Wood, K.L. Bio-inspired design: An overview investigating open questions from the broader field of design-by-analogy. *J. Mech. Des.* **2014**, *136*, 111102. [CrossRef]
15. Chakrabarti, A.; Sarkar, P.; Leelavathamma, B.; Nataraju, B. A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Artif. Intell. Eng. Des. Anal. Manuf.* **2005**, *19*, 113–132. [CrossRef]
16. Tan, R.; Liu, W.; Cao, G.; Shi, Y. Creative design inspired by biological knowledge: Technologies and methods. *Front. Mech. Eng.* **2019**, *14*, 1–14. [CrossRef]
17. Fayemi, P.-E.; Wanieck, K.; Zollfrank, C.; Maranzana, N.; Aoussat, A. Biomimetics: Process, tools and practice. *Bioinspiration Biomim.* **2017**, *12*, 011002. [CrossRef]
18. Ask Nature. Available online: https://asknature.org/ (accessed on 5 March 2020).
19. Bhasin, D.; McAdams, D.A.; Layton, A. A product architecture-based tool for bioinspired function-sharing. *J. Mech. Des.* **2021**, *143*, 081401. [CrossRef]
20. Zhang, P.; Li, X.; Nie, Z.; Yu, F.; Liu, W. A Trimming Design Method Based on Bio-Inspired Design for System Innovation. *Appl. Sci.* **2021**, *11*, 4060. [CrossRef]
21. Salgueiredo, C.F.; Hatchuel, A. Beyond analogy: A model of bioinspiration for creative design. *Ai Edam* **2016**, *30*, 159–170. [CrossRef]
22. Goel, A.K.; Hancock, W. Multifunctional and domain independent? A meta-analysis of case studies of biologically inspired design. *Des. Sci.* **2021**, *7*, E24. [CrossRef]
23. Wanieck, K.; Fayemi, P.-E.; Maranzana, N.; Zollfrank, C.; Jacobs, S. Biomimetics and its tools. *Bioinspired Biomim. Nanobiomater.* **2017**, *6*, 53–66. [CrossRef]
24. Versos, C.A.; Coelho, D.A. Biologically inspired design: Methods and validation. In *Industrial Design-New Frontiers*; IntechOpen: London, UK, 2011; pp. 101–120.
25. Design Spiral. Available online: https://biomimicry.org/biomimicry-design-spiral/ (accessed on 12 May 2020).
26. Lenau, T.A. Do biomimetic students think outside the box? In Proceedings of the DS 87-4 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 4: Design Methods and Tools, Vancouver, BC, Canada, 21–25 August 2017; pp. 543–552.
27. Baumeister, D.; Zari, M.P. 10 Biomimicry An opportunity for buildings to relate to place. In *Ecologies Design: Transforming Architecture, Landscape, and Urbanism*; Routledge: London, UK, 2020.
28. Vakili, V.; Chiu, I.; Shu, L.; McAdams, D.; Stone, R. Including functional models of biological phenomena as design stimuli. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, NV, USA, 4–7 September 2007; pp. 103–113.
29. Nagel, J.K. A thesaurus for bioinspired engineering design. In *Biologically Inspired Design*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 63–94.

30. Nagel, R.L.; Midha, P.A.; Tinsley, A.; Stone, R.B.; McAdams, D.A.; Shu, L. Exploring the use of functional models in biomimetic conceptual design. *J. Mech. Des.* **2008**, *130*, 121102. [CrossRef]
31. Nagel, J.K.; Schmidt, L.; Born, W. Establishing analogy categories for bio-inspired design. *Designs* **2018**, *2*, 47. [CrossRef]
32. Helms, M.; Goel, A.K. The four-box method: Problem formulation and analogy evaluation in biologically inspired design. *J. Mech. Des.* **2014**, *136*, 111106. [CrossRef]
33. Goel, A.K.; Vattam, S.; Wiltgen, B.; Helms, M. Information-processing theories of biologically inspired design. In *Biologically Inspired Design*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 127–152.
34. Vattam, S.S.; Helms, M.E.; Goel, A.K. Compound analogical design: Interaction between problem decomposition and analogical transfer in biologically inspired design. In *Design computing and cognition'08*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 377–396.
35. Hirtz, J.; Stone, R.B.; McAdams, D.A.; Szykman, S.; Wood, K.L. A functional basis for engineering design: Reconciling and evolving previous efforts. *Res. Eng. Des.* **2002**, *13*, 65–82. [CrossRef]
36. Nagel, J.K.; Stone, R.B.; McAdams, D.A. Function-based biologically inspired design. In *Biologically Inspired Design*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 95–125.
37. Vandevenne, D.; Verhaegen, P.-A.; Duflou, R.J. Mention and focus organism detection and their applications for scalable systematic bio-ideation tools. *J. Mech. Des.* **2014**, *136*, 111104. [CrossRef]
38. Lindsey Williams, M.; Ertas, A.; Tate, D. Using stochastic multicriteria acceptability analysis in biologically inspired design as a multidisciplinary tool to assess biology-to-engineering transfer risk for candidate analogs. *J. Mech. Des.* **2014**, *136*, 111107. [CrossRef]
39. Blösch-Paidosh, A.; Shea, K. Design heuristics for additive manufacturing. In *Proceedings of the DS 87-5 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 5: Design for X, Design to X*; Vancouver, BC, Canada, 21–25 August 2017, pp. 91–100.
40. Jacobs, S.R.; Nichol, E.C.; Helms, M.E. "Where are we now and where are we going?" The BioM innovation database. *J. Mech. Des.* **2014**, *136*, 111101. [CrossRef]
41. Tan, N.; Sun, Z.; Mohan, R.E.; Brahmananthan, N.; Venkataraman, S.; Sosa, R.; Wood, K. A system-of-systems bio-inspired design process: Conceptual design and physical prototype of a reconfigurable robot capable of multi-modal locomotion. *Front. Neurorobotics* **2019**, *13*, 78. [CrossRef]
42. Altshuller, G.; Al'tov, G.; Altov, H. *And Suddenly the Inventor Appeared: TRIZ, the Theory of Inventive Problem Solving*; Technical Innovation Center, Inc.: Worcester, MA, USA, 1996.
43. Badarnah, L.; Kadri, U. A methodology for the generation of biomimetic design concepts. *Archit. Sci. Rev.* **2015**, *58*, 120–133. [CrossRef]
44. Ren, L.; Liang, Y. Biological couplings: Classification and characteristic rules. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 2791–2800. [CrossRef]
45. Svendsen, N.W.; Lenau, T.A. Approaches to analyzing multi-functional problems. In *Proceedings of the DS 101: Proceedings of NordDesign 2020*; Lyngby, Denmark, 12–14 August 2020, pp. 1–12.
46. Svendsen, N.; Lenau, T.A. How does biologically inspired design cope with multi-functionality? In Proceedings of the Design Society: International Conference on Engineering Design, Delft, The Netherlands, 5–8 August 2019; pp. 349–358.
47. Wolff, J.O.; Wells, D.; Reid, C.R.; Blamires, S.J. Clarity of objectives and working principles enhances the success of biomimetic programs. *Bioinspiration Biomim.* **2017**, *12*, 051001. [CrossRef]
48. Bhasin, D.; McAdams, D.A. Current state of the art: Problem-driven multi-functional bio-inspired designs. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Anaheim, CA, USA, 18–21 August 2019; p. V007T006A020.
49. Langille, R. Human tissues and systems. *NSCC Hum. Biol.* **2020**, *1*, 12–13.
50. Adeliade, U.o. Essential Human Biology: Cells and Tissues. Available online: https://www.adelaide.edu.au/learning/adelaidex/free-online-courses/essential-human-biology-cells-and-tissues (accessed on 5 October 2022).
51. Gao, X. Antifogging Properties in Mosquito Eyes. In *Encyclopedia of Nanotechnology*; Bhushan, B., Ed.; Springer: Dordrecht, The Netherlands, 2012; pp. 117–121.
52. Ensikat, H.J.; Ditsche-Kuru, P.; Neinhuis, C.; Barthlott, W. Superhydrophobicity in perfection: The outstanding properties of the lotus leaf. *Beilstein J. Nanotechnol.* **2011**, *2*, 152–161. [CrossRef]
53. Tong, J.; Lü, T.-b.; Ma, Y.-h.; Wang, H.-k.; Ren, L.-q.; Arnell, R. Two-body abrasive wear of the surfaces of pangolin scales. *J. Bionic Eng.* **2007**, *4*, 77–84. [CrossRef]
54. Liu, Z.; Jiao, D.; Weng, Z.; Zhang, Z. Structure and mechanical behaviors of protective armored pangolin scales and effects of hydration and orientation. *J. Mech. Behav. Biomed. Mater.* **2016**, *56*, 165–174. [CrossRef] [PubMed]
55. Wang, B.; Sullivan, T.N. A review of terrestrial, aerial and aquatic keratins: The structure and mechanical properties of pangolin scales, feather shafts and baleen plates. *J. Mech. Behav. Biomed. Mater.* **2017**, *76*, 4–20. [CrossRef]
56. Gillis, J.A.; Alsema, E.C.; Criswell, K.E. Trunk neural crest origin of dermal denticles in a cartilaginous fish. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 13200–13205. [CrossRef]
57. Shen, J.; Xie, Y.M.; Huang, X.; Zhou, S.; Ruan, D. Mechanical properties of luffa sponge. *J. Mech. Behav. Biomed. Mater.* **2012**, *15*, 141–152. [CrossRef] [PubMed]

58. Gibson, P.L. Lecture 18, Nature Sandwich Notes, 3.0.54. Available online: https://ocw.mit.edu/courses/materials-science-and-engineering/3-054-cellular-solids-structure-properties-and-applications-spring-2015/lecture-notes/MIT3_054S15_L18_Nat_trans.pdf (accessed on 10 June 2020).
59. Gibson, L.J.; Ashby, M.; Easterling, K.E. Structure and mechanics of the iris leaf. *J. Mater. Sci.* **1988**, *23*, 3041–3048. [CrossRef]
60. Gibson, L.J.; Ashby, M.F.; Harley, B.A. *Cellular Materials in Nature and Medicine*; Cambridge University Press: Cambridge, UK, 2010.
61. Yu, C.; Liu, M.; Zhang, C.; Yan, H.; Zhang, M.; Wu, Q.; Liu, M.; Jiang, L. Bio-inspired drag reduction: From nature organisms to artificial functional surfaces. *Giant* **2020**, *2*, 100017. [CrossRef]
62. Chowdhury, H.; Islam, R.; Hussein, M.; Zaid, M.; Loganathan, B.; Alam, F. Design of an energy efficient car by biomimicry of a boxfish. *Energy Procedia* **2019**, *160*, 40–44. [CrossRef]
63. Garner, S.N.; Naleway, S.E.; Hosseini, M.S.; Acevedo, C.; Gludovatz, B.; Schaible, E.; Jung, J.-Y.; Ritchie, R.O.; Zavattieri, P.; McKittrick, J. The role of collagen in the dermal armor of the boxfish. *J. Mater. Res. Technol.* **2020**, *9*, 13825–13841. [CrossRef]
64. Hundertmark, C.; Tinter, R.; Ortelt, M.; Hauser, M.J. Diatom-inspired plastic deformation elements for energy absorption in automobiles. *J. Bionic Eng.* **2015**, *12*, 613–623. [CrossRef]
65. Korsunsky, A.M.; Bedoshvili, Y.D.; Cvjetinovic, J.; Aggrey, P.; Dragnevski, K.I.; Gorin, D.A.; Salimon, A.I.; Likhoshway, Y.V. Siliceous diatom frustules–A smart nanotechnology platform. *Mater. Today Proc.* **2020**, *33*, 2032–2040. [CrossRef]
66. McKeag, T. Auspicious Designs. Available online: https://issuu.com/eggermont/docs/zq_issue_02r_final (accessed on 5 May 2020).
67. Rico-Guevara, A.; Sustaita, D.; Gussekloo, S.; Olsen, A.; Bright, J.; Corbin, C.; Dudley, R. Feeding in birds: Thriving in terrestrial, aquatic, and aerial niches. In *Feeding in Vertebrates*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 643–693.
68. Nature, A. Horsetail Leaves. Available online: https://asknature.org/strategy/stems-vary-stiffness/ (accessed on 10 June 2020).
69. Velivela, P.T.; Letov, N.; Liu, Y.; Zhao, Y.F. Application of domain integrated design methodology for bio-inspired design-A case study of suture pin design. *Proc. Des. Soc.* **2021**, *1*, 487–496. [CrossRef]
70. Shah, J.J.; Smith, S.M.; Vargas-Hernandez, N. Metrics for measuring ideation effectiveness. *Des. Stud.* **2003**, *24*, 111–134. [CrossRef]
71. Nelson, B.A.; Wilson, J.O.; Rosen, D.; Yen, J. Refined metrics for measuring ideation effectiveness. *Des. Stud.* **2009**, *30*, 737–743. [CrossRef]
72. Linsey, J.S.; Clauss, E.F.; Kurtoglu, T.; Murphy, J.T.; Wood, K.L.; Markman, A.B. An experimental study of group idea generation techniques: Understanding the roles of idea representation and viewing methods. *J. Mech. Des.* **2011**, *133*, 031008. [CrossRef]
73. López-Forniés, I.; Sierra-Pérez, J.; Boschmonart-Rives, J.; Gabarrell, X. Metric for measuring the effectiveness of an eco-ideation process. *J. Clean. Prod.* **2017**, *162*, 865–874. [CrossRef]
74. Seepersad, C.C.; Pedersen, K.; Emblemsvåg, J.; Bailey, R.; Allen, J.K.; Mistree, F. The validation square: How does one verify and validate a design method. *Decis. Mak. Eng. Des.* **2006**, *1*, 303–314.
75. Schachinger, P.; Johannesson, H.L. Computer modelling of design specifications. *J. Eng. Des.* **2000**, *11*, 317–329. [CrossRef]
76. White, E.H.; Steinmetz, M.G.; Miano, J.D.; Wildes, P.D.; Morland, R. Chemi-and bioluminescence of firefly luciferin. *J. Am. Chem. Soc.* **1980**, *102*, 3199–3208. [CrossRef]
77. Leitão, J.M.; da Silva, J.C.E. Firefly luciferase inhibition. *J. Photochem. Photobiol. B Biol.* **2010**, *101*, 1–8. [CrossRef] [PubMed]
78. David Morgan, E. Trail pheromones of ants. *Physiol. Entomol.* **2009**, *34*, 1–17. [CrossRef]
79. Klowden, M.J. *Physiological Systems in Insects*; Academic Press: Cambridge, MA, USA, 2013.