TECHNISCHE UNIVERSITÄT MÜNCHEN
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Bionik als systematische Methodik für Produktentwicklung und Innovation

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Abkürzungsverzeichnis

BID .... *Biologically-inspired design*, biologisch-inspiriertes Design

BIOPS .... *Biology inspired problem solving*

BOS .... *Blue-Ocean*-Strategie

CATPCA ..... *Categorical Principal Components Analysis,* Kategorische Mehrkomponentenanalyse

FT .... Forschungsthema

ISO .... *International Organization for Standardization*

KMU .... Kleine und mittelständische Unternehmen

MVP .... *Minimum viable produc*t

PoC .... *Proof of Concept*

SKO .... *Soft kill option*

TC .... *Technical Committee*

TRIZ .... Russisches Akronym für sinngemäß *Theorie des erfinderischen Problemlösens*

VDI .... Verein Deutscher Ingenieure

1. Einleitung

Technologie und Innovation sind zentrale Handlungsfelder der modernen Gesellschaft und ihrer Wirtschaft. Die Umsetzung von Innovation ist dabei eng mit dem wissenschaftlich-technischen Fortschritt verknüpft und sie kann zum gesellschaftlichen Wohlstand beitragen. In der Entwicklung technischer Produkte geht es daher auch darum, innovative Ideen umzusetzen oder Probleme in bestehenden Produkten zu lösen, um diese zu verbessern und den Markt zu erreichen. Dabei verfolgt der Entwickler das Ziel, das Produkt den festgelegten Anforderungen, z. B. in seinen Funktionen, Funktionalitäten oder Formen anzupassen. Nicht immer ist dabei die spezifische Lösung sofort erkennbar oder sie ist durch technische oder organisatorische Restriktionen nur eingeschränkt umsetzbar. Darüber hinaus bedeutet Produktentwicklung auch, etwas Neues zu schaffen (Lindemann, 2009), insbesondere wenn es darum geht, dem Innovationsdruck gerecht zu werden, unter dem sich Unternehmen befinden (Vahs, 2013). Der Entwickler benötigt daher für seine Lösungs- oder Ideenfindung Ansätze, die es ihm ermöglichen, neue Ideen zu generieren oder Barrieren für die Lösungsfindung zu überwinden. Ein Ansatz, den er dafür zusätzlich in seiner klassischen Entwicklungsarbeit einsetzen kann, ist die Bionik – das Lernen von der Natur für die Lösung technischer Probleme.

Die Bionik ist als Wissenschaftsdisziplin seit einigen Jahrzehnten etabliert und hat neue Möglichkeiten eröffnet, insbesondere technische Produkte zu verbessern (Lepora et al., 2013; Vincent et al., 2006; von Gleich et al., 2007). Die Biodiversität mit ihren rund 1,5 Millionen beschriebenen Arten reflektiert eine Vielzahl an Formen, Materialien, Funktionen, Prozessen, Prinzipien und Strukturen, mit denen sich Organismen oder Populationen an sich verändernde Umwelt- und Lebensbedingungen angepasst haben (Snell-Rood, 2016). In der Theorie können diese Strategien für das Lösen praktischer Probleme genutzt werden, indem Erkenntnisse, die an biologischen Vorbildern gewonnen werden, als Modelle abstrahiert und auf die jeweilige Problemstellung übertragen werden (ISO/TC 266, 2015)[1]. Die Erkenntnisse aus der Biologie sind u. a. durch wissenschaftliche Publikationen verfügbar, deren Anzahl im Bereich der Bionik einem wachsenden Trend folgt und im Jahr 2013 bei rund 3000 Veröffentlichungen pro Jahr lag (Lepora et al., 2013). Und dieser Trend setzt sich fort (Lenau et al., 2018a). Das Potenzial der Bionik als Methode für die Lösung technischer Probleme und als Basis für Innovation wird daher als immens eingestuft. Sie gilt als eine führende Denkweise für die Entwicklung neuer Technologien, welche Wissenschaft, Wirtschaft und Gesellschaft in Zukunft bedeutend beeinflussen wird (Ferdinand et al., 2012; Gebeshuber et al., 2009; Lepora et al., 2013).

Während dieses Potenzial nachvollziehbar klingt, stellt sich die Frage, wie es praktisch für Produktentwicklung und Innovation genutzt werden kann. Die vorliegende Arbeit befasst sich an der Schnittstelle von wissenschaftlicher Bionik-Forschung und industrieller Anwendung mit der Bionik als Problemlösungsstrategie und betrachtet als primäre Zielgruppe Entwickler und Ingenieure in der Industrie.

1.1 Problemstellung und Forschungsfrage

Die Bionik hat grundsätzlich zwei allgemeine Vorgehensweisen, den so genannten lösungsbasierten (*solution-based,* Badarnah and Kadri, 2015; Helms et al., 2008; *Bottom-Up,* Speck und Speck, 2008) und den problemgetriebenen Ansatz (*problem-driven,* Helms et al., 2008; Vattam, S. et al., 2007; *Top-Down* (Speck und Speck, 2008). Der lösungsbasierte Prozess beschreibt eine technische Entwicklung, die auf einer zufällig entdeckten oder bekannten Lösung aus der Natur basiert. Im Gegensatz dazu beschreibt der problemgetriebene Prozess die gezielte Lösungssuche in der Natur für eine technische Problemstellung. Im Kontext von Produktentwicklung und Innovation könnte man annehmen, dass Unternehmen primär die problemgetriebene Vorgehensweise nutzten, um gezielt unternehmensinterne Fragestellungen und Probleme durch den Einsatz von Bionik zu lösen bzw. Lösungsansätze zu generieren. In einer Studie über biologisch inspirierte Produkte von Jacobs et al. war diese Vorgehensweis allerdings unterrepräsentiert: So wurden rund 33% der beschriebenen Produkte über den problemgetriebenen und 67% über den lösungsbasierten Prozess entwickelt (Jacobs et al., 2014).

[1] Das Technische Komitee (*TC: Technical Committee*) der internationalen Organisation für Normung ISO (*International Organization for Standardization)* befasst sich mit der Entwicklung internationaler Standards für die Bionik.

Im Gegensatz zu dem beschriebenen technologischen Potenzial der Bionik ist die Zahl der als von der Natur inspirierten Produkte mit weltweit 379 dokumentierten Fällen überschaubar (Jacobs et al., 2014) und erscheint gegenüber der Fülle an Wissen, welches aus der Biologieforschung für die Bionik theoretisch zur Verfügung steht, überraschend gering. Bei schätzungsweise 9 Millionen existierenden eukaryotischen Arten hat die Forschung im Kontext der Bionik das Wesentliche der biologischen Inspiration noch unberücksichtigt gelassen (Snell-Rood, 2016).

In zwei unabhängigen Studien wurde bereits ermittelt, dass die Bionik in der Regel auf die Initiative und das Engagement einzelner Personen oder Forschungs- und Entwicklungseinrichtungen zurückzuführen sei. Weder national noch international sei die kritische Masse für die Bionik bereits erreicht, um den Innovationsprozess maßgeblich zu gestalten. Es wird deutlich gemacht, dass die bionische Herangehensweise nachhaltig in den Innovationsprozess der Industrie integriert werden müsse. Es werde zukünftig auch darauf ankommen, das Wissen aus bereits geleisteter Forschungsarbeit an die nächste Bionik-Generation weiterzugeben und vor allem durch Ausbildung einen Multiplikatorenprozess anzustoßen. Die bionische Denkweise müsse stärker in Bildung und Ausbildung integriert werden. Bionik biete einen geeigneten Rahmen für einen gezielten und effizienten Wissenstransfer von der Grundlagenforschung bis hin zur technischen Anwendung. Vom damaligen Standpunkt aus betrachtet wurde die Bionik als eine Technologieoption mit immensem Potenzial eingestuft (Oertel und Grunwald, 2006; von Gleich et al., 2007).

Die Gründe, weshalb bisher nicht mehr Wissen aus der Natur in die technische Entwicklung von Produkten einfließt, sind vielfältig. Dabei wird unter anderem das Fehlen einer Methodik aufgeführt (Jacobs et al., 2014; Vincent et al., 2006). Die Befragung von Unternehmen im Rahmen einer dieser Arbeit zugrundeliegenden Bachelorarbeit zeigt zudem, dass von 14 befragten Unternehmen 21% bisher kein passendes Projekt identifizieren konnten und dass bei 50% gar kein bzw. nur ein eingeschränktes Wissen über Bionik als Problemlösungsstrategie vorliegt (Ritzinger, 2015). Das Fehlen einer geeigneten Bewertungsstrategie über den möglichen Einsatz von Bionik für eine bestimmte Fragestellung und der Mangel einer existierenden praxisorientierten Vorgehensweise könnten Gründe sein, weshalb die Bionik allgemein und der problemgetriebene Prozess im Speziellen bisher in der Anwendung hinter ihrem Potenzial zurückliegen.

Goel et al. postulieren, die vielversprechende Denkweise der Bionik für Innovation und Nachhaltigkeit müsse in eine reproduzierbare und skalierbare Methodik umgewandelt werden, und bezeichnen dies als wissenschaftliche Herausforderung. Darüber hinaus müssten dabei zahlreiche große Herausforderungen bearbeitet werden, zu denen insbesondere die folgenden vier zählen (Goel et al., 2014):

(1) die Bearbeitung von realen Problemen mit daraus resultierenden Produkten am Markt,
(2) die Dokumentation der Verfahren von Erfolgsbeispielen (*Best practices*), um daraus eine Theorie des *Biologically-inspired design* (BID)[2] zu entwickeln,
(3) die Entwicklung von rechenbetonten Methoden und Werkzeugen für die Reproduzierbarkeit und Skalierbarkeit der Methodik und
(4) die Ausbildung einer neuen Generation von zukünftigen Designern bzw. Entwicklern.

An diesen Herausforderungen setzt die vorliegende Arbeit an. Im Hinblick auf die beschriebene Diskrepanz zwischen dem bekannten Potenzial der Bionik und der Anzahl daraus resultierender Innovationen wurde die folgende Forschungsfrage definiert:

> **Wie muss der Prozess der Bionik gestaltet sein, um effizient in der Industrie, insbesondere auch in kleinen und mittelständischen Unternehmen (KMU), eingesetzt werden zu können?**

Diese Forschungsfrage ist speziell auf den Prozess der Bionik im Bereich Produktentwicklung und Innovation ausgerichtet.[3]

Insbesondere im Bereich des Innovationsmanagements gibt es verschiedene Möglichkeiten und Herangehensweisen für das Lernen von der Natur, die im Folgenden näher betrachtet werden. Die Bionik im klassischen Sinne folgt einer forschungsbasierten Vorgehensweise (ISO/TC 266, 2015) und beschreibt den Wissenstransfer aus der Biologie in die Praxis. Sie kann als Kreativitätstechnik und Innovationsprozess verstanden werden, erfordert i. d. R. aber grundlagen- oder anwendungsorientierte Forschung, um im Sinne ihrer Definition im internationalen Standard ISO 18458 ihr Potenzial auszuschöpfen (ISO/TC 266, 2015). Darüber hinaus gibt es andere Konzepte, wie z. B. Biomimicry (Baumeister et al., 2013; Benyus, 2008) oder BID (Goel et al., 2014), die in ihrer Durchführung Ähnlichkeiten zur Bionik aufweisen und die in der Forschung der vorliegenden Arbeit mit berücksichtigt werden.

[2] Der Begriff *Biologically-inspired design* wird von Goel et al. (2014) so verwendet, wobei die beschriebenen Herausforderungen auch für die Bionik gelten und daher hier Bezug genommen wird. Auf die unterschiedliche Bedeutung der Terminologie und daraus resultierende Schwierigkeiten wird in den Abschnitten 3.2 und 4.1 eingegangen.
[3] Weitere Anwendungsmöglichkeiten und die Übertragung der Ergebnisse der vorliegenden Arbeit auf diese Bereiche werden in Kapitel 4 diskutiert.

Betrachtet man die Bionik im Kontext von Produktentwicklung und Innovation, dann lässt sich die Definition der Bionik konzeptionell erweitern, indem man die Bionik versteht als:

1. Eine Wissenschaftsdisziplin, die auf Grundlagen- und anwendungsorientierter Forschung basiert und den Wissenstransfer zwischen Biologie und Technik zum Ziel hat (Bionik, ISO/TC 266, 2015; Lepora et al., 2013).

   Beispiel: Entwicklung von bionischen Materialien, z. B. trockene Adhäsion inspiriert durch den Gecko (Lee et al., 2007)

2. Eine Problemlösungsstrategie als Teil des problemgetriebenen Produktentwicklungsprozesses (Eggermont, 2008; Fayemi et al., 2017; ISO/TC 266, 2015).

   Beispiel: Selbstschärfende Messer inspiriert durch Nagetierzähne
   (Kaiser, M. K. et al., 2014)

3. Eine Vorgehensweise zur Entwicklung neuer Ideen und Produkte (als Teil von 2.) oder zum Neudenken eines Produktes (*Blue Ocean*-Strategie (BOS); lösungsbasierter Prozess der Bionik)[4] als Kreativitätstechnik oder als systematische Vorgehensweise, basierend auf Katalogen oder biologischen Prinzipien.

   Beispiel: Biologische Materialien mit scharfen Kanten
   (Meyers et al., 2008)

4. Ein Mittel zur Entwicklung nachhaltiger Lösungen (Antony et al., 2014; Benyus, 2008; Mead und Jeanrenaud, 2017; Reap und Bras, 2014; Speck et al., 2017), z. B. basierend auf material- und energieeffizienten Systemen.

   Beispiel: Materialeffiziente Strukturen durch *Soft Kill Option* (SKO) (Baumgartner et al., 1992)

5. Eine Innovationsstrategie (Bertling, 2014)

   Beispiel: *Bionic Learning Network* der Festo AG & Co. KG
   ("Bionic Learning Network")

Der Prozess der Bionik ist ein mehrdimensionaler Multikomponenten-Prozess, dessen Anwendungsmöglichkeiten vielfältig sind. Darüber hinaus gestaltet sich seine Anwendung und

[4] Unter einem "blauen Ozean" versteht man unberührte Marktbereiche, in denen der Wettbewerb irrelevant ist und in denen man neue Nachfrage weckt und bedient. Das Unternehmen geht damit neue innovative Wege und schafft sich einen eigenen Markt (Kim und Mauborgne, 2005). Im übertragenen Sinn kann entsprechend einer BOS eine geeignete Vorgehensweise beschrieben werden, um systematisch für technisch, gesellschaftlich, ökologisch oder wirtschaftlich interessante Phänomene der Natur Anwendungsfelder in Industrie und Gesellschaft zu identifizieren. Dieser Bezug wird in Kapitel 5 (S. 40) näher erläutert.

Integration ins unternehmerische Umfeld auf verschiedenen Ebenen komplex, was in Abbildung 1 vereinfacht dargestellt ist.

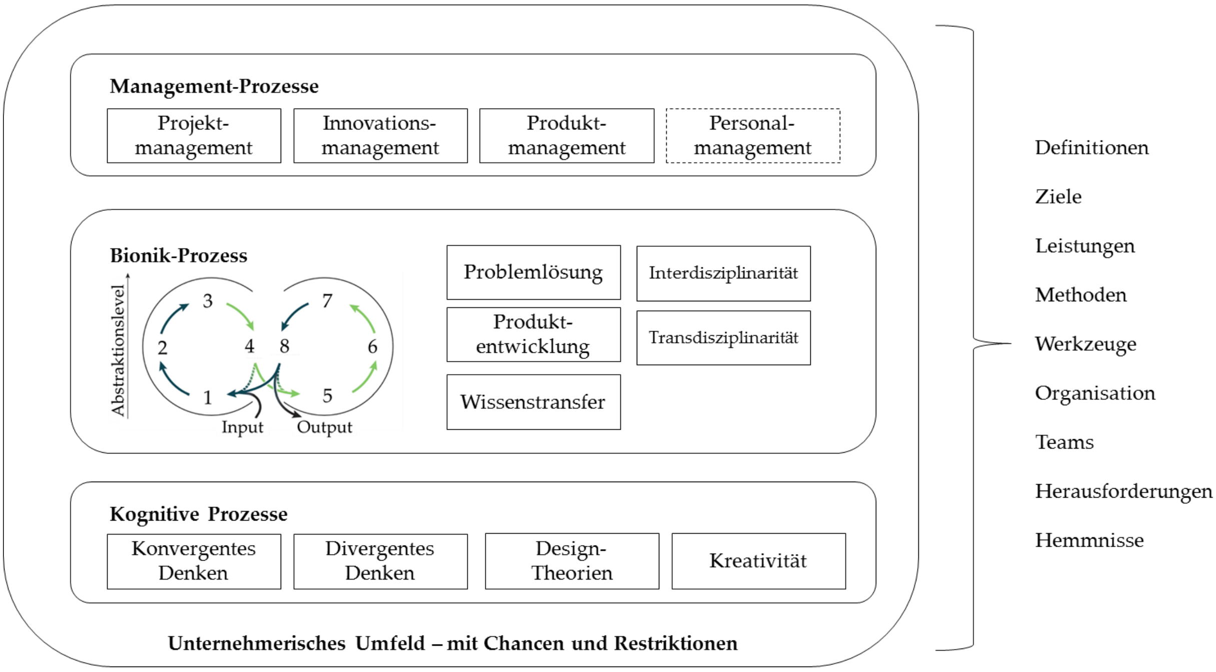

Abbildung 1: Dimensionen und Komponenten der Bionik in Unternehmen. Die Personalentwicklung ist im Rahmen dieser Arbeit nicht betrachtet worden, es gibt aber auch dort Ansätze der biologischen Inspiration (Fox, 2017). 1-8 beschreiben die Schritte des problemgetriebenen Bionik-Prozesses nach Fayemi et al. (2017): 1: Problemanalyse, 2: Problemabstraktion, 3: Übertragung in die Biologie, 4: Suche biologischer Vorbilder, 5: Auswahl geeigneter Vorbilder, 6: Abstraktion der Biologie, 7: Übertragung in die Technik, 8: Anwendung und Tests

So lässt sich die Bionik in verschiedenen Bereichen einsetzen, indem sie beispielsweise die klassische Produktentwicklung oder Problemlösung ergänzt. Dabei müssen spezifische Aufgaben erfüllt werden, was mit bekannten Schwierigkeiten verbunden ist (Linsey et al., 2010; Linsey und Viswanathan, 2014; Nagel et al., 2016; Wanieck et al., 2017; Yen et al., 2014). Darüber hinaus kann die Bionik mit bestehenden Managementprozessen verknüpft werden sowie unternehmensinterne oder externe Disziplinen einbeziehen. Sowohl akademische als auch nicht akademische Partner können und müssen ggf. integriert werden. Des Weiteren wird der Prozess der Bionik durch kognitive Prozesse begleitet, die effektiv gesteuert und trainiert werden können.

Diese Aspekte sowie die verschiedenen Herangehensweisen und Anwendungspotenziale von Bionik für Produktentwicklung und Innovation erfordern zur Beantwortung der Forschungsfrage eine umfassende Forschung, die insbesondere auch die von Goel et al. (2014) erwähnten vier großen Herausforderungen einbezieht. Tabelle 1 fasst die Forschungsthemen zusammen, die in der vorliegenden Arbeit untersucht werden.

Tabelle 1: Forschungsthemen und ihre Bedeutung im Prozess der Bionik. Die Tabelle zeigt die verschiedenen Themen, die in der vorliegenden Arbeit behandelt werden und sich z. T. noch in weiterer Bearbeitung befinden. FT: Forschungsthema

	Thema	**Fragestellungen und Bezug zum Prozess der Bionik**	**Bearbeitung in der vorliegenden Arbeit**
FT 1	Prozessbeschreibungen	Welche Prozessbeschreibungen gibt es? Worin unterscheiden sie sich? Lässt sich eine einheitliche Beschreibung definieren?	ja in Kooperation mit der *Arts et Métiers ParisTech*, Frankreich
FT 2	Bezug zur klassischen Entwicklungsarbeit in Unternehmen	Welcher Bezug besteht zur klassischen Produktentwicklung und Problemlösung?	ja in Kooperation mit der *Arts et Métiers ParisTech*, Frankreich
FT 3	Herausforderungen bei Durchführung, Entwicklung und Vermarktung von Produkten	Was kann man von Fallstudien lernen? Wie lässt sich das *Valley of death*[5] der Produktentwicklung überwinden?	ja in Kooperation mit der *University of Guelph*, Kanada
FT 4	Lehre, Ausbildung und Training des Prozesses	Wie wird der Prozess gelehrt? Welche Bedeutung haben die einzelnen Lehrziele?	ja
FT 5	Werkzeuge und Methoden	Welche Werkzeuge existieren, die den Prozess unterstützen, und wie werden sie eingesetzt? Welchen Einfluss hatten sie bisher auf die Produktentwicklung? Wie können sie für Lehre und Training genutzt werden?	ja
FT 6	Nutzbarkeit von Werkzeugen	Welche Anforderungen gibt es an die Werkzeuge? Wie lassen sie sich messen und bewerten? Welche Werkzeuge werden aktuell und in Zukunft benötigt?	ja z.T. in Kooperation mit der *Arts et Métiers ParisTech*, Frankreich laufende Forschung

[5] Der Ausdruck *Valley of death* umfasst u. a. allgemeine Herausforderungen von Innovationen sowie die Schwierigkeiten in der Zusammenarbeit von akademischer Forschung und industrieller Anwendung (Bhushan, 2015).

	Thema	Fragestellungen und Bezug zum Prozess der Bionik	Bearbeitung in der vorliegenden Arbeit
FT 7	Weiterentwicklung der Methodik	Wie kann die Bionik als systematische Methode beschrieben werden? Lassen sich Werkzeuge integrieren, die die Anwendung unterstützen?	ja z.T. in Kooperation mit der *Arts et Métiers ParisTech*, Frankreich
FT 8	Nutzergruppen	Welche verschiedenen Nutzergruppen und ihre Anforderungen an den Prozess gibt es? Wie müssen Lehre und Ausbildung gestaltet sein?	ja
FT 9	Teamzusammensetzung	Welche Rollen gibt es in Bionik-Teams? Wie muss das Teammanagement gestaltet sein?	aktuelle Forschung in Kooperation mit der *University of Malta* und der *Arts et Métiers ParisTech*, Frankreich

Bei der Durchführung von Bionik und ihrer zugrundeliegenden Prozesse spielen Denkprozesse und individuelle kognitive Fähigkeiten der Nutzer eine entscheidende Rolle für den Erfolg der Entwicklungsarbeit (Stricker, 2006). Diese Aspekte wurden in der vorliegenden Arbeit nicht explizit betrachtet, werden aber in Kapitel 4 diskutiert.

Die Motivation für die Betrachtung der Bionik als systematischer und reproduzierbarer Prozess und dessen Unterstützung durch existierende Werkzeuge entstand aus der langjährigen Zusammenarbeit mit Vertretern der Industrie in verschiedenen Projekten. Es wurde deutlich, dass den Bionik-Prozess unterstützende Werkzeuge sowohl in der Industrie als auch in der Fachgemeinschaft der Bionik weitestgehend unbekannt sind. Daher war die Erforschung der Themen FT1 (Prozessbeschreibungen) und FT5-FT7 (Werkzeuge & Methoden, Nutzbarkeit von Werkzeugen, Methodik) von zentraler Bedeutung. Dabei stand der Wissenstransfer biologisch-inspirierter Lösungen für Produktentwicklung und Innovation im Vordergrund, mit dem Ziel, eine effiziente Methode als Problemlösungsstrategie zu entwickeln und die Bionik als Methodik zu betrachten.

1.2 Zielsetzung der Arbeit

Strukturierte Prozesse können helfen, die Innovationsfähigkeit von Unternehmen zu stärken (Gassmann und Granig, 2013). Abbildung 2 zeigt vereinfacht den Weg eines Produktes von der Idee über das Konzept hin zum Markteintritt. Die vorliegende Arbeit ist auf den Prozess der Bionik in der Produktentwicklung ausgerichtet, betrachtet aber auch in Ansätzen die weiteren notwendigen Schritte für eine erfolgreiche Innovation, welche per Definition den Markteintritt und die Etablierung des Produktes am Markt erfordert. Dazu zählen beispielsweise geeignete Wege der Kommerzialisierung oder passende Geschäftsmodelle, die frühzeitig in Projekten betrachtet werden sollten.

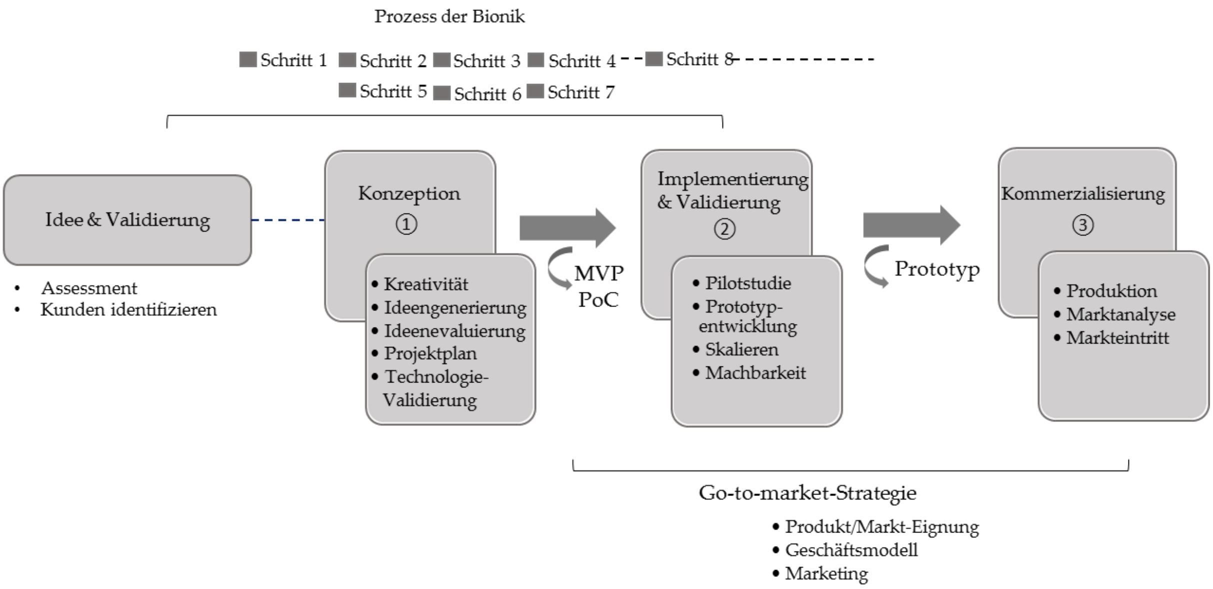

Abbildung 2: Phasen des Innovationsprozesses und die Verbindung zu den acht Schritten des Bionik-Prozesses nach Fayemi et al. (2017). Schritt 1: Problemanalyse, Schritt 2: Problemabstraktion, Schritt 3: Übertragung in die Biologie, Schritt 4: Suche biologischer Vorbilder, Schritt 5: Auswahl geeigneter Vorbilder, Schritt 6: Abstraktion der Biologie, Schritt 7: Übertragung in die Technik, Schritt 8: Anwendung und Tests. ①, ②, ③ bezeichnen die Hauptphasen eines vereinfachten Innovationsprozesses. MVP: *Minimum viable product*; PoC: *Proof of Concept* (verändert nach Chirazi et. al, 2019)

Die vorliegende Arbeit hat daher zum Ziel, den Prozess der Bionik zu strukturieren und so zu gestalten, dass Unternehmen diesen als Methodik in der täglichen, klassischen Produktentwicklung und zur Gestaltung von Innovationen einsetzen können. Der Begriff Innovation umfasst verschiedene Arten und Dimensionen (Hauschildt und Salomo, 2007). In der vorliegenden Arbeit wird der Begriff primär für eine neuartige Produktentwicklung genutzt, die sich am Markt durchgesetzt hat.

Als langfristiges Ziel der Arbeit sollen neue Erkenntnisse über den Prozess der Bionik dazu beitragen, ihr Potenzial für die Problemlösung verstärkt zu nutzen und biologisch-inspirierte

Innovationen entwickeln zu können. Dadurch sollten in Zukunft vermehrt biologisch-inspirierte Produkte auf den Markt gelangen können. Zum anderen soll ein Beitrag dazu geleistet werden, den Erfolg von Produktentwicklungen reproduzierbar zu gestalten und die Methodik der Bionik effektiv vermitteln und lehren zu können.

Die vorliegende Arbeit entstand im Rahmen mehrerer Forschungsprojekte an der Technischen Universität München und der Technischen Hochschule Deggendorf. Die Ergebnisse entstanden zum Teil in internationalen Kooperationen mit der *Arts et Métiers ParisTech*, Frankreich, und, der *University of Guelph*, Kanada.

2. Methoden

Zur Bearbeitung der Forschungsfrage und ihrer angrenzenden Themen wurden verschiedene Methoden eingesetzt, die im Folgenden beschrieben werden.

2.1 Literaturrecherchen

Zu den Forschungsthemen FT1 (Prozessbeschreibungen), FT4 (Lehre), FT5 (Werkzeuge) und FT8 (Nutzergruppen) wurden Literaturrecherchen in der wissenschaftlichen Fachliteratur durchgeführt. Ziel dieser Recherchen war

- die Analyse der Literatur zu Prozessbeschreibungen, Werkzeugen und Lehrangeboten (FT1, FT4, FT5),
- die Analyse von Lücken in der Literatur und von zu bearbeitenden Fragestellungen,
- die Identifizierung und Gegenüberstellung verschiedener Prozessbeschreibungen (FT1),
- die Identifizierung und Zusammenfassung vorhandener Werkzeuge und Methoden für den Prozess der Bionik (FT5),
- die Identifizierung und Kategorisierung von Themen, Lehrzielen, Inhalten, Intensitäten, Erfahrungen und Zielgruppen von Lehr- und Trainingsangeboten (FT4),
- die Identifizierung verschiedener Nutzergruppen (FT8) für den Prozess der Bionik.

Für die Recherchen wurden verschiedene Suchbegriffe verwendet, die das breite Feld der Bionik und des BID abdecken. Dazu zählten u. a. die Begriffe „biomimetics“, „biomimicry“, „biologically-inspired design“ und “bionic(s)” in Kombination mit Begriffen wie „tools“, „methods“, „education“, „teaching“, „training“, „class“, „course“ oder „case studies“ . Die webbasierte Suche in Fachzeitschriften und Konferenzbeiträgen war aus den folgenden Gründen bei der jeweiligen Suche nur eingeschränkt erfolgreich:

- Lehrangebote, Werkzeuge oder Prozessbeschreibungen stammen aus verschiedenen Disziplinen und die verschiedenen verwendeten Begriffe zerstreuen die Literatur.
- Es gibt bisher keine einheitlich verwendeten Schlagworte, um Literatur zu kennzeichnen.
- Nicht alle bekannten Lehrinhalte oder Werkzeuge konnten über die Literatursuche identifiziert werden.
- Bekannte Werkzeuge oder Lehrinhalte sind in der Literatur nicht beschrieben.

Daher wurde die Literaturrecherche durch das Schneeballprinzip per Hand ergänzt, um eine möglichst umfassende Zusammenstellung von Suchergebnissen zu erzielen. Bei der Recherche aktueller Lehrangebote wurden auch Institutionen aus zwei Berichten berücksichtigt („Proceedings: Biomimicry in Higher Education Webinar, 2012"; „CEEBIOS – Bericht"), wenn sie ausreichend Informationen zu den entsprechenden Fragestellungen auf ihrer Webseite zur Verfügung stellten. Die entsprechenden Webseiten sind in der Literatur mit aufgeführt.

2.2 Interviews

Es wurden Interviews mit Firmenvertretern aus Deutschland geführt, welche bereits über erste Projekterfahrungen mit Bionik verfügten (Ritzinger, 2015). Die Interviewpartner hatten entweder a) ein Bionik-Produkt auf dem Markt, b) ein Bionik-Produkt in der Entwicklung bzw. auf der Stufe eines Prototyps oder c) sie hatten an einem Workshop für Bionik teilgenommen und verfügten über erste Erfahrungen in der Produktentwicklung durch Bionik.
Die Interviews umfassten 30 offene oder geschlossene Fragen und wurden durchgeführt, um die Bedürfnisse und Interessen von Nutzern im Kontext der Bionik zu verstehen. Dazu waren die Interviews in fünf Teile aufgeteilt:

1. Allgemeine Informationen zum Unternehmen
2. Bisheriges Vorgehen im Bereich systematische Innovation
3. Interdisziplinarität und Netzwerke der Innovation
4. Bionik
5. Nachhaltigkeit

Die Interviews wurden an 21 Firmen verschickt, von denen 14 mit einem vollständigen Interview antworteten. Die Interviews wurden durch einen Bacheloranden geführt und ausgewertet (Ritzinger, 2015). Darüber hinaus wurden die der *BioM Innovation Database* (Jacobs et al., 2014) zugrunde liegenden Interviews mit weltweit angesiedelten Firmen analysiert und ausgewertet (n=69). Die Interviews umfassten u. a. Fragen zum:

a) Produktentwicklungsprozess,
b) Bionik-Prozess im Speziellen (z. B. Art und Charakteristika des biologischen Vorbildes),
c) zur Interdisziplinarität,
d) zu den Zeitpunkten der Entwicklung (u. a. Konzept, Prototyp, Markteintritt) und
e) zur Nachhaltigkeit.

Die Daten der Interviews aus der *BioM Innovation Database* sind inhomogen, als dass einige Fragen wegen fehlender Information oder Geheimhaltung von Daten unbeantwortet blieben. Daher wurden die Interviews entsprechend der zur Verfügung gestellten Informationen kombiniert, um vergleichbare Daten zu erhalten.

Die insgesamt vorhandenen 83 Interviews wurden im Hinblick auf

- den Prozess der Produktentwicklung,
- die Interdisziplinarität der Teams,
- die Entwicklungszeiten der Projekte,
- die Nutzung von Werkzeugen in den Projekten sowie
- die Erfolge und Herausforderungen der Projekte analysiert.

Nur jene Interviews, die einen gemeinsamen vergleichbaren Datensatz für die jeweiligen Forschungsthemen enthielten, wurden zusammengefasst und ausgewertet. Die erzielten Ergebnisse beziehen sich daher jeweils auf entsprechende Teilgruppen der Interviews.

Die Ergebnisse der Interviews wurden für die Bearbeitung der Fragestellungen FT 1 (Prozessbeschreibungen), FT 3-5 (Herausforderungen, Lehre, Werkzeuge) und FT9 (Teamzusammensetzung) verwendet.

2.3 Workshops

Für die Bearbeitung der Forschungsthemen FT 6-8 (Nutzbarkeit von Werkzeugen, Methodik, Nutzergruppen) wurde in Kooperation mit der *Arts et Metiers ParisTech,* am Lehrstuhl *Innovation and Product Design Laboratory* ein Workshop gemeinsam durchgeführt und ausgewertet. Zwei weitere Workshops wurden durch den Kooperationspartner geleitet. Die Autorin der vorliegenden Arbeit leitete den Test von vier Werkzeugen aus der Bionik-und Design-Forschung (*Functional Modelling of Biology*, Nagel et al., 2011; *Four-Box-Method*, Helms und Goel, 2014; BIOPS - *BIOlogy inspired problem solving*, "BIOPS"; BionIQuity, Dell, 2006).

Diese Werkzeuge wurden hinsichtlich ihrer Entwicklung und/oder Beschreibung in der wissenschaftlichen Fachliteratur als geeignet eingestuft, um in realen Industrie-Projekten eingesetzt werden zu können.
Für die jeweiligen Workshops wurden den Teilnehmern die ausgewählten Werkzeuge vorgestellt und erklärt. Dazu wurde für jedes Werkzeug eine Schulung erarbeitet, die

- den theoretischen Hintergrund als allgemeine Einführung enthielt,
- ein erklärendes Beispiel für die Anwendung des Werkzeugs präsentierte sowie
- eine Übung im Umgang mit dem Werkzeug umfasste.

Die Schulung dauerte je nach Werkzeug und Anforderung eine bis zwei Stunden. Die Auswahl der jeweiligen Werkzeuge erfolgte hinsichtlich ihrer Zuordnung zu den vier Phasen des Bionik-Prozesses (Analyse, Abstraktion, Transfer und Anwendung). Außerdem wurden nur jene Werkzeuge ausgewählt, die sich wie beschrieben vorstellen und einsetzen ließen.

Im Verlauf des Workshops testeten die Teilnehmer diese Werkzeuge bei der Bearbeitung einer konkreten Problemstellung. Im Anschluss teilten sie ihre Erfahrungen in einer Evaluierung mit. Die Evaluierung der einzelnen Werkzeuge umfasste insgesamt 17 theoretische und sechs praktische Kriterien (Fayemi et al., 2017). Dazu zählten beispielsweise die Eignung des Werkzeugs für die Fragestellung, die Fähigkeit funktionale Modelle zu bilden (Abstraktionswerkzeuge) oder die Folgerichtigkeit der Ergebnisse (Transferwerkzeuge).
Ziel der durchgeführten Workshops war es,

- den Einsatz von Werkzeugen im Prozess der Bionik zu analysieren,
- die Nutzbarkeit ausgewählter Werkzeuge an praktischen Beispielen zu testen,
- die Erfahrungen in der Anwendung durch Nutzer zu eruieren.

Die Ergebnisse der Workshops wurden durch den Kooperationspartner mittels eines Wilcoxon-Vorzeichen-Rang-Tests statistisch ausgewertet (Fayemi et al., 2017). Die geringe Datenmenge ist eine Limitation der Auswertung und erlaubt keine robusten quantitativen Aussagen. Die Ergebnisse wurden allerdings genutzt, um Trends und qualitative Aussagen zu treffen.

2.4 Qualitative und semi-quantitative Analysen

Die Ergebnisse der Literaturrecherchen und die Daten aus den Interviews wurden hinsichtlich ihrer Relevanz für die einzelnen Forschungsthemen qualitativ analysiert und semi-quantitativ ausgewertet.

2.4.1 Prozessbeschreibungen

Die identifizierten Prozessbeschreibungen der Bionik wurden in Bezug auf ihre einzelnen Prozessschritte qualitativ analysiert und verglichen. Darüber hinaus wurden sie mit den fünf Schritten des klassischen Problemlösungsprozesses in Verbindung gesetzt: Identifikation des Problems, Definition des Problems, Ideengenerierung, Auswahl der Lösung sowie Anwendung und Test (Fayemi et al., 2017; Massey und Wallace, 1996). Ziel der Analyse war es,

- die Bionik-Problemlösung mit der klassischen Problemlösung zu vergleichen,
- Rückschlüsse über spezifische Aspekte der Bionik-Problemlösung zu ziehen,
- die einzelnen notwendigen Schritte des Bionik-Problemlösungsprozesses zu identifizieren sowie
- einen vereinheitlichten Prozess für die problemgetriebene Vorgehensweise der Bionik zu beschreiben.

Darüber hinaus wurde untersucht, inwiefern sich die einzelnen Schritte der vereinheitlichten Prozessbeschreibung mit Werkzeugen unterstützen lassen. Dazu wurden die recherchierten Werkzeuge klassifiziert, was im nächsten Abschnitt beschrieben wird.

2.4.2 Klassifizierung von Werkzeugen und Methoden

Für die Beschreibung vorhandener Werkzeuge im Prozess der Bionik (FT5, FT6) wurden die recherchierten Werkzeuge deskriptiv analysiert und mithilfe von Anwendungsfaktoren (Variablen) klassifiziert. Insgesamt wurden zehn Variablen definiert, die jeweils nominale oder ordinale Kategorien zur Klassifizierung umfassten. Die Variablen sind in Tabelle 2 zusammengefasst.

Die Klassifizierung der identifizierten Werkzeuge ermöglicht:

- eine Aussage über die Bedeutung der Werkzeuge für den lösungsbasierten und problemgetriebenen Prozess der Bionik,
- die Zuordnung der jeweiligen Werkzeuge zu den einzelnen Schritten der entwickelten vereinheitlichten Prozessbeschreibung,
- den Vergleich der Werkzeug-Typen im Prozess der Bionik,
- die Auswahl geeigneter Werkzeuge für die jeweiligen Prozessschritte,
- eine Aussage über den Bezug zur Nachhaltigkeit bei Verwendung der Werkzeuge.

Tabelle 2: Variablen und Kategorien zur qualitativen Klassifizierung von Werkzeugen der Bionik.
DSK: Datenbank, statische Liste, Katalog

Variable	Kategorie	Ausprägung
v1: Klasse	Abstraktion Anwendung Analyse Transfer	Nominal
v2: Typ	DSK Taxonomie Thesaurus Ontologie Algorithmus Methode	Nominal
v3: Prozessschritt	Schritt 1 Schritt 2 Schritt 3 Schritt 4 Schritt 5 Schritt 6 Schritt 7 Schritt 8	Ordinal
v4: Vorgehensweise	Lösungsbasiert Problemgetrieben	Nominal
v5: Zugänglichkeit	Open-source Eingeschränkt Kommerziell	Ordinal
v6: Verfügbarkeit	Online Software Druck	Nominal
v7: Wissensbereich	Biologie Technik Biologie und Technik	Nominal
v8: Dimension	Alleinstehend Benötigt vorherigen Schritt Unterstützt nachfolgenden Schritt Benötigt vorherigen Schritt und unterstützt nachfolgenden Schritt	Ordinal
v9: Nachhaltigkeit	Ja Nein	Nominal
v10: Nachweis der Wirksamkeit	Ja Nein	Nominal

2.4.3 Ziele und Inhalte in Lehr- und Trainingsangeboten

2.4.3.1 Übersicht

Die recherchierten und identifizierten Lehrangebote wurden im Hinblick auf die internationale Verteilung, ihre Inhalte und Zielsetzungen analysiert. Diese wurden mit der Absicht zusammengefasst, um

- das steigende Interesse an der Ausbildung nachfolgender Generationen zu erforschen,
- die Vielfältigkeit sowie Unterschiede in den Lehrmethoden zu analysieren,
- Muster in den Konzepten zu identifizieren (Struktur und Inhalt),
- wesentliche Lehrinhalte und -ziele zu extrahieren und
- zukünftige Bereiche der Weiterentwicklung zu identifizieren.

2.4.3.2 Klassifizierung

Hinsichtlich der Lehrziele von Angeboten wurden aus den Daten zentrale Lehrziele zusammengefasst und mittels der Taxonomie-Tabelle, welche auf der Bloom's Taxonomie basiert (Krathwohl, 2002), auf ihre Bedeutung hin untersucht. Die Taxonomie-Tabelle ermöglicht es, die Gewichtung von Lehrinhalten zu bestimmen, Lehrpläne zu erstellen und anzupassen sowie bisher versäumte Lehrmöglichkeiten zu identifizieren (Krathwohl, 2002). Durch diese Vorgehensweise können Empfehlungen für zukünftige Lehrangebote in Bionik ausgesprochen werden.

Dazu wurden die Lehrziele entsprechend der Dimensionen der Taxonomie-Tabelle klassifiziert (Krathwohl, 2002): die *Wissens-Dimension* (A. Faktisches Wissen, B. Konzeptionelles Wissen, C. Prozedurales Wissen , D. Meta-kognitives Wissen) und die *Kognitiver Prozess-Dimension* (1. Erinnern, 2. Verstehen, 3. Anwenden, 4. Analysieren, 5. Evaluieren, 6. Erschaffen). Im Falle der Überschneidung eines Lehrziels mit mehreren möglichen Dimensionen der Tabelle wurde die niedrigste Dimension ausgewählt, sodass die Zuordnung zu anderen höheren Dimensionen möglich ist.

2.4.4 Zielgruppenanalyse

Für die Zielgruppenanalyse in Lehr- und Trainingsangeboten wurden Personae skizziert. Personae repräsentieren eine Gruppe von Nutzern, die detaillierte Charakteristika aufweisen, konkrete Ziele besitzen und ein Bedürfnis für spezifische Informationen haben (Albers, 2003). Da die Entwicklung und Definition von Personae nicht einheitlich definiert ist, wurden auch Aspekte der Daten-basierten Entwicklung (McGinn und Kotamraju, 2008) mit einbezogen.

Dazu wurden zum einen qualitative Rückschlüsse aus den Daten der identifizierten Lehrangebote gezogen, und zum anderen wurden die vorliegenden Interviews analysiert. Bei den Interviews wurden Angaben über

- die Position der Befragten im Unternehmen,
- den fachlichen Hintergrund der Befragten,
- die Motivation für Bionik im Unternehmen,
- die Erfahrungen im interdisziplinären Arbeiten und
- aufgetretene Schwierigkeiten während der Entwicklung

ausgewertet.

2.4.5 Produktentwicklungen

Für die Bearbeitung von FT3 (Herausforderungen bei Durchführung, Entwicklung und Vermarktung) wurden die Daten der *BioM Innovation Database* (Jacobs et al., 2014) sowie von Studien der *University of California*, San Diego ("Biomimicry Business Summary Report") über erfolgreich am Markt angekommene Produkte analysiert. Zusätzlich wurden die von Ritzinger (2015) durchgeführten Interviews im Hinblick auf die Forschungsfragen ausgewertet.

Die Daten wurden genutzt, um

- die Entwicklung von Patenten,
- den Kommerzialisierungsprozess von Produkten,
- die benötigte Zeit für die Entwicklung eines Produktes von der Idee bis zur Markteinführung,
- die beiden Entwicklungswege der Bionik (lösungsbasiert, problemgetrieben),
- die Herausforderungen der Produktentwicklung sowie
- die Erfolgsfaktoren der Entwicklung

zu analysieren. Darüber hinaus wurde eine Verbindung zu den Forschungsthemen FT2 (klassische Entwicklung) und FT7 (Methodik) hergestellt.

3. Ergebnisse

3.1 Beschreibung der Veröffentlichungen

Die zwei zentralen Forschungsthemen in der vorliegenden Arbeit und die daraus abgeleiteten Aufgaben sind die Erforschung (a) der Prozessbeschreibung der Bionik und (b) der vorhandenen Werkzeuge, die den Prozess unterstützen können. Das Ziel dieser Forschungsleistung ist es, zunächst einen Überblick existierender Werkzeuge und Methoden zu erstellen. Darüber hinaus sollen die Ziele, Erfolge, Herausforderungen und Verbindungen existierender Werkzeuge und Methoden durch eine Klassifizierung und Analyse beschrieben werden.

Die Ergebnisse der Forschung über den Prozess und die Werkzeuge der Bionik sind in den ersten beiden Veröffentlichungen zusammengefasst (Fayemi et al., 2017; Wanieck et al., 2017). Die dritte Veröffentlichung wurde von der Autorin federführend erstellt und befasst sich mit den erforderlichen Schritten von einem Bionik-Konzept hin zu einem erfolgreichen Markteintritt und stellt eine Verbindung zum klassischen Innovationsmanagement her (Chirazi et al., 2019).

Des Weiteren wurde ein Artikel verfasst, der sich zum Zeitpunkt der Abgabe der vorliegenden Arbeit im Einreichungsprozess befindet. Dieser Artikel beschreibt die notwendigen Anforderungen an erfolgreiche Lehre und Ausbildung im Kontext der Bionik. Ergebnisse daraus werden in Abschnitt 3.2 zusammengefasst.

1. **Wanieck K., Fayemi P.E., Maranzana N., Zollfrank C. and Jacobs S. (2017): Biomimetics and its tools. Bioinspired, Biomimetic and Nanobiomaterials 6 (2), 53-66**

Die Veröffentlichung „*Biomimetics and its tools*" befasst sich mit der Problemstellung, dass Nutzer der Bionik bei deren praktischer Anwendung im unternehmerischen Umfeld vor zum Teil unüberwindbaren Herausforderungen stehen. Diese Schwierigkeiten sind seit der Professionalisierung der Bionik bekannt und weltweit haben Forscher an den verschiedenen Problemen und Herausforderungen gearbeitet. In diesem Zusammenhang wurden Werkzeuge entwickelt, die Nutzer der Bionik unterstützen, die einzelnen notwendigen Schritte zu vollziehen. Diese Werkzeuge stammen aus den verschiedensten Fachrichtungen und Disziplinen, wie u. a. Bionik, Ingenieurwissenschaften, Informatik oder Design. Demzufolge sind diese Werkzeuge sowohl der Fachgemeinschaft als auch dem Nutzer weitestgehend unbekannt, da sie verstreut über verschiedene Fachbereiche beschrieben sind. Die Veröffentlichung möchte diesen Werkzeugen zu größerer Bekanntheit verhelfen sowie ihre Stärken und Schwächen aufzeigen, um die Weiterentwicklung von Werkzeugen, ihren Einsatz im Prozess der Bionik und letztendlich die biologisch-inspirierte Produktentwicklung zu fördern. Dazu präsentiert das Manuskript eine Übersicht von 43 recherchierten Werkzeugen sowie eine Klassifizierung mit qualitativen deskriptiven Kriterien. Mithilfe dieser Klassifizierung und der Einteilung der Werkzeuge zu den jeweiligen Prozessschritten der Bionik kann der Nutzer leicht erkennen, bei welcher Problemstellung er auf eines der Werkzeuge zurückgreifen kann. Zum anderen wird deutlich, bei welchen Prozessschritten der Bionik ein Bedarf an neuen Werkzeuge bzw. eine Weiterentwicklung vorhandener Werkzeuge vorliegt.

Die Autorin der vorliegenden Arbeit hat das Forschungsthema identifiziert und das Konzept für die Veröffentlichung erstellt. Sie entwickelte die Methodik zur Analyse von Werkzeugen und hat die entsprechenden Daten erhoben und analysiert sowie die Ergebnisse visualisiert. Sie hat die Texte verfasst und mit den Co-Autoren abgestimmt. Der Begutachtungsprozess wurde von ihr geleitet.

2. Fayemi P.E., Wanieck K., Zollfrank C., Maranzana N. and Aoussat A. (2017): Biomimetics: process, tools and practice, Bioinspiration & Biomimetics 12, 011002

Die Veröffentlichung „*Biomimetics: process, tools and practice*" ist parallel zu der ersten Veröffentlichung und in enger Kooperation mit dem erstgenannten Autor entstanden. Beide Erstautoren haben gleichermaßen zur Veröffentlichung beigetragen.

Die Veröffentlichung richtet sich primär an Nutzer der Bionik im industriellen Umfeld und die Forschung basiert auf der Annahme, dass Nutzer Herausforderungen in der Anwendung haben, die bisher nicht genügend adressiert wurden. Das Ziel der Arbeit ist es, Unklarheiten in Bezug auf Definitionen und Prozessbeschreibungen der Bionik zu beseitigen. Daher werden zunächst Definitionen der Bionik und ihre Wirkungstiefe aufgezeigt. Im Folgenden werden verschiedene Prozessbeschreibungen der Bionik verglichen und zu einem Modell zusammengefasst, welches sich an den Schritten der klassischen Problemlösung orientiert und den Prozess der Bionik in acht Schritte untergliedert. Diese Schritte der Bionik können durch spezielle Bionik-Werkzeuge und allgemeine Design- Werkzeuge unterstützt werden. Eine Auswahl vorhandener Werkzeuge wurde für den Prozess der Bionik gewählt und in Workshops sowie während einer Konferenz getestet. Die Teilnehmer haben die theoretischen und praktischen Charakteristika der Werkzeuge evaluiert. Die Veröffentlichung präsentiert eine statistische Auswertung der Evaluation. Basierend auf diesen Ergebnissen wird zum Schluss der Entwurf eines Entscheidungsbaums präsentiert. Dieser leitet der Nutzer durch den Prozess der Bionik und schlägt anhand entsprechender Fragen die Auswahl geeigneter Werkzeuge vor. Die Ergebnisse dieser Veröffentlichung sollen die praktische Anwendung der Bionik und somit langfristig die Anzahl biologisch-inspirierter Produkte erhöhen.

Die Arbeit entstand während eines Forschungsaufenthaltes als Gastwissenschaftlerin an der *Arts et Métiers ParisTech*, Frankreich. Dabei hat die Autorin der vorliegenden Arbeit aktiv an der Forschung sowie an den Ergebnissen für die Veröffentlichung mitgewirkt. Sie hat die Auswahl der Werkzeuge mitgestaltet sowie einen der Workshops geleitet. Sie hat an der Gestaltung des Entscheidungsbaumes mitgewirkt, Konzept, Inhalte und Struktur der Veröffentlichung mitbestimmt und große Teile des Artikels geschrieben.

3. **Chirazi, J.; Wanieck, K.; Fayemi, P.-E.; Zollfrank, C.; Jacobs, S. What Do We Learn from Good Practices of Biologically Inspired Design in Innovation? Applied Sciences 2019, 9, 650.**

Die Veröffentlichung betrachtet den Prozess der Bionik von der Konzeptentwicklung eines Produktes bis hin zur Markteinführung und stellt eine Verbindung her zwischen der klassischen Produktentwicklung und den Charakteristika der Bionik. Es ist eine erste Fallstudie von rund 100 Produkten, die sich detailliert mit dem Entwicklungsprozess und den Erfahrungen der Entwickler auseinandersetzt. Sie beschreibt die Erfolgsfaktoren von Produktbeispielen und schlägt Schlüsselschritte vor, die für eine erfolgreiche Kommerzialisierung von Bionik-Produkten notwendig sind. Letztendlich soll die Veröffentlichung dazu beitragen, das Verständnis des Bionik-Prozesses im Kontext von Innovation zu vertiefen und somit langfristig wirtschaftliches Wachstum und nachhaltige Innovation zu vereinen.

Zunächst wird das technologische Potenzial der Bionik aufgezeigt, indem insbesondere eine Verbindung zum Innovationsprozess, Design-Methoden und der klassischen Entwicklung hergestellt wird. Die Wege, die Bionik-Produkte theoretisch einschlagen können, von der Neuentwicklung bis zur Gründung von neuen Unternehmen, werden beschrieben. Die vorhandene Diskrepanz zwischen dem technologischen Potenzial und der Anzahl biologisch inspirierter Produkte am Markt leitet über zur Bedeutung der Bionik im Kontext von Innovation. So wird verdeutlicht, dass wesentliche Aspekte im Entwicklungsprozess von Bionik-Produkten berücksichtigt werden müssen, um messbare Erfolge zu erzielen. Dass dabei Schwierigkeiten auftreten und welchen Herausforderungen sich Entwickler stellen müssen, wird in der Abbildung des „*Valley of Death*" in Innovationen beschrieben. Um diese Herausforderungen zu überwinden, werden im Weiteren die Ergebnisse aus Interviews und Fallstudien präsentiert. Von diesen sollen Entwickler lernen können, um Bionik im eigenen unternehmerischen Kontext anwenden zu können. Die Ergebnisse geben Aufschluss über die Entwicklungszeiten von erfolgreichen Produkten, wie viele Patente aus Konzepten entstanden sind und welche Herausforderungen und Erfolgsfaktoren existieren. Neben praktischen Empfehlungen zeigt die Veröffentlichung auch weiteren Forschungsbedarf auf.

Die Autorin der vorliegenden Arbeit hat das Thema der Veröffentlichung identifiziert, definiert und die Inhalte des Manuskripts zusammengestellt. Sie hat die Struktur des Manuskripts erstellt und die Rohdaten ihrer Co-Autoren ausgewertet und visualisiert. Außerdem hat sie die Texte verfasst, mit ihren Co-Autoren abgestimmt und den Begutachtungsprozess geleitet. Die beiden Erstautoren haben gleichermaßen zur Veröffentlichung beigetragen.

3.2 Lehr- und Trainingsangebote: Ziele, Inhalte und Zielgruppen

Für die Transformation der Bionik hin zu einer verlässlichen Methodik ist die Ausbildung einer neuen Generation von zukünftigen Designern bzw. Entwicklern notwendig (Goel et al., 2014). In der vorliegenden Arbeit wird daher analysiert, welche Lehrangebote es in öffentlichen und privaten Programmen gibt, welche Lehrziele und -inhalte dabei im Vordergrund stehen und wie sich Pläne für das Erlernen der Methodik gestalten lassen.

Tabelle 3 fasst unterschiedliche Themen zusammen, die aktuell im Kontext der Bionik gelehrt werden. Die Vielfalt der Themen verdeutlicht erneut, wie wichtig eine klare Definition und das Verständnis für Bionik und andere angrenzende Ansätze sind. Der internationale Standard ISO 18458 ist diesbezüglich das am weitesten fortgeschrittene Dokument, auf das man sich beziehen kann (ISO/TC 266, 2015). Einige Begriffe fehlen zwar, wie z. B. *biologisch inspirierte Innovation*[6], und es ist anzunehmen, dass sich weitere Themen entwickeln werden, wie man z. B. an den Begriffen *Biologische Transformation*[7] oder *Biologisierung*[8] sieht. Trotzdem bietet der Standard einen Rahmen, der sich zukünftig weiterentwickeln wird.

Die beschriebenen Ziele der untersuchten Lehrangebote können in 18 Haupt-Lehrzielen zusammengefasst werden, deren Übersicht sich in Tabelle 4 findet. Die Lehrziele verdeutlichen unterschiedliche Aspekte, die in der Ausbildung adressiert werden:

a) Die persönliche Motivation (Lehrziele 3, 4, 11),
b) ein solides Verständnis für den Bionik-Prozess, seine Grundlagen und Anwendung (Lehrziele 1, 2, 5, 6, 7, 8),
c) Fähigkeiten, die man bei der Anwendung von Bionik erlangt (Lehrziele 12-17),
d) das Management von Bionik-Projekten (Lehrziel 10) und
e) eine zukünftige Expertise, diese Thematik anwenden und erklären zu können (Lehrziele 9, 18).

Damit ist Bionik sowohl als eigenes Fachgebiet als auch als ein Werkzeug für die interdisziplinäre Ausbildung zu verstehen (Yen et al., 2011).

[6] Dieser Begriff wird als Titel eines Master-Studiengangs an der Utrecht University verwendet ("Bio Inspired Innovation").
[7] Die Fraunhofer Gesellschaft verwendet diesen Begriff in einem 2018 veröffentlichten Grundlagenpapier ("Biologische Transformation und Bioökonomie").
[8] Das Fraunhofer Institut für Umwelt-, Sicherheits- und Energietechnik verwendet diesen Begriff als Leitbild ihrer Forschungspolitik ("Biologisierung").

Tabelle 3: Themen von Lehrangeboten im Kontext der Bionik und angrenzender Ansätze. BID: *Biologically-inspired design*; TRIZ: *Theorie des erfinderischen Problemlösens*

Thema	Titel des Lehrangebotes	Quelle
Biomimetics	Biomimetics	("Biomimetics (B.Sc)"; Eggermont, 2008)
	Biomimetic design	(Cheong et al., 2014; Glier et al., 2011)
	Biomachines and Biomimetics	("Biomachines and Biomimetics")
	Biomimetics Motion Systems	("Biomimetics Motion Systems")
	Konstruktionsbionik	("Konstruktionsbionik")
Biomimicry	Biomimicry	("Green Harbors Project - Biomimcry"; 'Nagel, J. K. S. und Stone, R. B., 2011; Rowland, 2017)
	Biomimicry for Designers	("Biomimicry for Designers")
	Biomimicry: From life to nanotechnological innovations	(Cleymand et al., 2015)
Bio*-inspired*	BID	(Helms et al., 2009; Jeannette et al., 2010; Nagel et al., 2016; Nelson et al., 2009; Yen et al., 2011)
	BID of sport	(Santulli and Langella, 2011)
	Bio-inspired engineering	(Jenkins, 2011)
	Bio-inspired innovation	("Bio Inspired Innovation")
	Bio-inspired robotics	(Bruck et al., 2007, 2006, 2004)
	Bioinspired materials	("Bioinspired Materials ǀ Doctoral training")
Bionics	Bionics	("Bionics")
	Bionics engineering	("Bionics Engineering")
	Bionics/biomimetics	("Bionics/Biomimetics, M.Sc.")
	Material Design - Bionics and Photonics	("Material Design - Bionics and Photonics")
	Science communication and bionics	("Science Communication & Bionics")
Sonstige	Bio-TRIZ	(Vincent, 2016)
	Integrating Biology and Design for Sustainable Innovation	(Kennedy et al., 2015)

Die einzelnen Themen der Lehrangebote könnten z. T. eher die Forschungsinteressen der jeweiligen Autoren und ihrer Institutionen widerspiegeln als die Tiefe der Lehre. Darüber hinaus existieren sicherlich weitere Lehrangebote, die nicht berücksichtigt sind. Eine umfassende Übersicht erfordert eine weltweite Recherche aller Lehreinrichtungen und ihrer Studienangebote, was beispielsweise schon aufgrund von sprachlichen Barrieren kaum realisierbar ist. Trotzdem erscheint eine solche Übersicht informativ und repräsentativ, da sie zeigt, wie vielfältig das Lehrangebot ist und dass es verschiedene Lehrmöglichkeiten gibt.

Tabelle 4: Hauptlehrziele von Lehrangeboten im Kontext der Bionik und angrenzender Ansätze.

Lehrziele		**Quelle**
Lehrziel 1	Ein solides Verständnis für Bionik und andere Ansätze haben (Gemeinsamkeiten und Unterschiede)	(“Green Harbors Project - Biomimcry”; Lehrziel aus Vorlesungen der Autorin)
Lehrziel 2	Eine umfassendere Wissensbasis haben	(Bruck et al., 2006)
Lehrziel 3	Die eigene Expertise für Bionik einsetzen	Lehrziel aus Vorlesungen der Autorin
Lehrziel 4	Einen persönlichen Zugang zu der Thematik finden (durch verschiedene Motivationen, wie Nachhaltigkeit, Innovationsmanagement, Entwicklung, Kreativität)	Lehrziel aus Vorlesungen der Autorin
Lehrziel 5	Die Muster, Strategien und Lösungen der Natur für analoge Probleme entdecken und erforschen	(“Biomachines and Biomimetics”; “Biomimicry 3.8”;)
Lehrziel 6	Den konzeptionellen Prozess lernen, der zu einem biologisch-inspirierten/Bionik-Design führt	(Santulli und Langella, 2011; Lehrziel aus Vorlesungen der Autorin)
Lehrziel 7	Den prozeduralen Prozess lernen, der zu einem biologisch-inspirierten/Bionik-Design führt	Lehrziel aus Vorlesungen der Autorin
Lehrziel 8	Werkzeuge und Methoden für biologisch-inspiriertes Design/Bionik lernen und einsetzen	(“Biomimicry”; Glier et al., 2011; Santulli und Langella, 2011; Lehrziel aus Vorlesungen der Autorin)
Lehrziel 9	Lebenslange Probleme durch Bionik bearbeiten, indem kreative, innovative Ideen und Lösungen entwickelt werden (neu und divers; ggf. nachhaltig und widerstandsfähig)	(“Green Harbors Project - Biomimcry”; Nelson et al., 2009; Lehrziel aus Vorlesungen der Autorin)
Lehrziel 10	Bionik-Projekte planen und managen	Lehrziel aus Vorlesungen der Autorin
Lehrziel 11	Eine Bionik-Denkweise entwickeln	(“Green Harbors Project - Biomimcry”)
Lehrziel 12	Integrative Fähigkeiten entwickeln	(“Biomimicry”; Eggermont, 2008)
Lehrziel 13	Kognitive Flexibilität entwickeln	(“Biomimicry”; Nagel et al., 2016, 2017)
Lehrziel 14	Kreativität trainieren	(Nagel et al., 2016, 2017)
Lehrziel 15	Anpassungsfähige Problemlösungsfähigkeiten entwickeln	(Nagel et al., 2016, 2017)
Lehrziel 16	Disziplinübergreifendes Denken	(Nagel et al., 2016, 2017)
Lehrziel 17	Über disziplinäre Grenzen hinweg und in interdisziplinären Teams arbeiten, sich einbringen, kommunizieren und zusammenarbeiten	(“Biomimicry 3.8”; Eggermont, 2008; Kennedy et al., 2015)
Lehrziel 18	Die Thematik, Arbeitsweisen und Herstellungsmethoden der Bionik verschiedenen Zielgruppen erklären	(“Biomachines and Biomimetics"; “Green Harbors Project - Biomimcry”)

Tabelle 5 zeigt die Klassifizierung der beschriebenen Lehrziele mithilfe der Taxonomie-Tabelle (Krathwohl, 2002). Durch diese Einteilung werden Lücken im Aufbau derzeitiger Lehre deutlich, welche sich durch eine Erweiterung der Lehrinhalte schließen lassen können.

Tabelle 5: Klassifizierung von Hauptlehrzielen der Lehrangebote im Kontext der Bionik. Die Lehrziele wurden nach der Taxonomie Tabelle nach Krathwohl (2002) klassifiziert.

	Kognitiver Prozess-Dimension					
Wissens-Dimension	**1. Erinnern**	**2. Verstehen**	**3. Anwenden**	**4. Analysieren**	**5. Evaluieren**	**6. Erschaffen**
A. Fakten-Wissen		Lehrziel 1				
B. Konzeptionelles Wissen		Lehrziel 2 Lehrziel 5 Lehrziel 6 Lehrziel 8				
C. Prozedurales Wissen		Lehrziel 7	Lehrziel 8	Lehrziel 9		Lehrziel 10 Lehrziel 12 Lehrziel 15
D. Metakognitives Wissen		Lehrziel 18	Lehrziel 17	Lehrziel 3	Lehrziel 4	Lehrziel 11 Lehrziel 13 Lehrziel 14 Lehrziel 16

Tabelle 5 verdeutlicht, dass in derzeitigen Lehrangeboten der Fokus auf dem *Verstehen des Konzeptes (B2)* und auf der *Kreierung von Lösungen (D6)* liegt. Dabei sind insbesondere kognitive Prozesse notwendig, die das Lernen und Lehren der Bionik zu einer anspruchsvollen Aufgabe machen.
Die Bionik basiert darüber hinaus auf neu zu erlernenden inter- und transdisziplinären Fähigkeiten, sodass das akademische Umfeld für transdisziplinäres Lernen angepasst werden könnte (Jacobs et al., 2017). Die freien Felder in Tabelle 5 zeigen zudem, dass es weitere Lehrmöglichkeiten gibt, die bisher unterrepräsentiert waren. Dazu könnten u. a. zählen:

1. Evaluation und Assessment von Problemen (A5, B5)
Hierbei stellt sich die Frage, welche Probleme mit Bionik grundsätzlich bearbeitet werden können. Dies ist insbesondere aus Sicht des Nutzers in der Praxis von Interesse und sollte vor Beginn eines Projektes geklärt werden.

2. Evaluation von erfolgreichen Schritten (C5)
Da der Prozess der Bionik iterativ ist und verschiedene Wissenskanäle einbezieht, könnten Studenten den Erfolg von Zwischenergebnissen stärker evaluieren. Eine der Herausforderungen innerhalb des Prozesses sind die Abstraktion von Biologie und Technik und

das Vermeiden des 1:1-Transfers von biologischen Phänomenen in die technische Anwendung (Yen et al., 2014). Wenn Evaluationsschritte eingebaut werden, könnte sich das Lernergebnis effektiver erzielen lassen.

3. Evaluation und Assessment von Lösungen (B5, C5)

Es gibt verschiedene Möglichkeiten, das Ergebnis von Bionik-Projekten zu klassifizieren, z. B. hinsichtlich der Einstufung als Bionik oder verwandte Ansätze (ISO/TC 266, 2015; Speck et al., 2017) oder in Bezug auf den Beitrag zur Nachhaltigkeit (Antony et al., 2014; de Pauw et al., 2015). Eine solche Bewertung könnte ein wertvoller Beitrag sein für die Inhalte der Lehre, um erzielte Ergebnisse und die Wirkmächtigkeit der Bionik besser einschätzen zu können.

Die Interviews mit 14 Unternehmen (5 KMU, 9 Großunternehmen) zeigen, dass 57% von ihnen nach eigener Einschätzung keine ausreichende Expertise in Bionik haben, um diese als Problemlösungsstrategie einzusetzen (Ritzinger, 2015). Dies verdeutlicht erneut die Notwendigkeit einer skalierbaren und robusten Methodik, die systematisch erlernt werden kann. Basierend auf den gesamten Interviews und den Ergebnissen der Literaturrecherche lassen sich Personae skizzieren. Exemplarische Beispiele daraus sind in Tabelle 6 dargestellt.

Tabelle 6. Exemplarische Personae im Kontext der Bionik und zugeordnete Lehrziele.

Position im Unternehmen	Charakteristika	Lehrziele
Bionik-Enthusiast	Ist von dem Thema fasziniert. Unternimmt eigene Recherchen. Würde die Thematik gerne im Unternehmen etablieren. Hat viele Ideen. Hat wenig bis viel Wissen über die Thematik. Kontaktiert Experten zur Hilfe.	1, 2, 6-10, 11, 17, 18
Projektleiter	Hat wenig bis viel Wissen über die Thematik. Ist bereit, die Thematik mit speziellen Fragestellungen zu testen. Weiß, wie man die Thematik einsetzen könnte. Übernimmt das Projektmanagement.	1, 2, 3, 6, 7, 9, 10, 11, 14, 15, 17, 18
Geschäftsführer	Hat wenig bis viel Wissen über die Thematik. Muss überzeugt werden. Sieht langfristige Chancen. Möchte schnelle Resultate. Ist bereit, Zeit und Geld zu investieren, wenn das Projekt realisierbar und rentabel ist.	2, 11, 18

Position im Unternehmen	Charakteristika	Lehrziele
Entwickler	Hat umfassende Erfahrung in seiner Arbeit. Hat der Thematik gegenüber Zweifel, ist aber offen dafür. Wird ein Projekt unterstützen, wenn es nicht zu viel Mehrarbeit bedeutet.	1, 2, 3, 5, 6, 7, 8, 10, 11, 13-17
Innovations-/Produktmanager	Möchte die Thematik für innovative neue Produkte nutzen. Sieht das Potenzial für Alleinstellungsmerkmale. Nutzt die Thematik zur Inspiration und für erste Analogien. Hat noch kein passendes Projekt identifiziert.	1, 2, 6-10, 11, 15, 18

Die beschriebenen Personae weisen auf Bedürfnisse und Erwartungen gegenüber den Lehrinhalten und –zielen hin. Daher sind die in Tabelle 4 beschriebenen Lehrziele den Personae zugeordnet. Die jeweiligen Anforderungen an die Ausbildung und Lehre können sich durch weitere Aspekte differenzierter beschreiben lassen, wie z. B. die Zuordnung einer Person zu einem KMU oder Großunternehmen oder wenn sich die berufliche Position einer Person ändert. Auch weitere Personae existieren sicherlich. Da Personae immer eine Gruppe von Personen umfasst, sind Variationen impliziert. Darüber hinaus lassen sich Personae für Studierende ableiten, welche in zukünftigen Arbeiten entwickelt werden.

Die beschriebenen Ergebnisse zeigen Aspekte des aktuellen Stands in der Lehre und Ausbildung von Nutzern im Kontext der Bionik, ihre Bedürfnisse sowie Möglichkeiten zum Anpassen von Lehrinhalten. Dies kann dazu beitragen, den Prozess der Bionik effektiv an nachfolgende Generationen weiterzugeben und damit zur Entwicklung einer robusten Methodik beizutragen.

4. Diskussion

Der Ausgangspunkt für die Forschung der vorliegenden Arbeit ist die Diskrepanz zwischen dem bekannten Potenzial der Bionik mit ihrem bedeutenden Beitrag für Innovation, Technik, Wirtschaft, Gesellschaft und Wissenschaft (Bertling, 2014; Ferdinand et al., 2012; Lepora et al., 2013; von Gleich et al., 2007) und dem Einfluss, den die Bionik bisher erzielt hat - gemessen an der Anzahl entwickelter Produkte, die in der wissenschaftlichen Literatur dokumentiert sind (Jacobs et al., 2014). Um den Einfluss der Bionik bewerten zu können, gibt es aktuell keine einheitliche Methodik. Als Variablen, die man überprüfen kann, werden u. a. die Anzahl von Produkten, Patenten, Veröffentlichungen oder Fördermitteln genutzt (Lenau et al., 2018a; Lepora et al., 2013). So versuchen vergangene und aktuelle Studien die Bedeutung der Bionik zu ermitteln und Handlungsempfehlungen für die Zukunft auszusprechen (Ferdinand et al., 2012; Jacobs et al., 2014; Lenau et al., 2018b; von Gleich et al., 2007).

Die vorliegende Arbeit befasst sich daher mit dem Prozess der Bionik als Vorgehensweise für die Entwicklung von Produkten und Innovationen. Abbildung 3 fasst die Ergebnisse vereinfacht zusammen.

Die Ergebnisse haben es ermöglicht, einen Bionik-Prozess zu beschreiben, der sich im unternehmerischen Umfeld sowie für die Ausbildung von Studierenden einsetzen lässt und der auch für die akademische Bionik-Forschung von Interesse sein kann. Die Bionik kann dabei eigenständig als Methodik aufgefasst werden oder sie kann die klassische Entwicklungsarbeit ergänzend unterstützen. Im Folgenden werden die Ergebnisse themenübergreifend eingeordnet und diskutiert sowie zukünftige Arbeiten aufgezeigt.

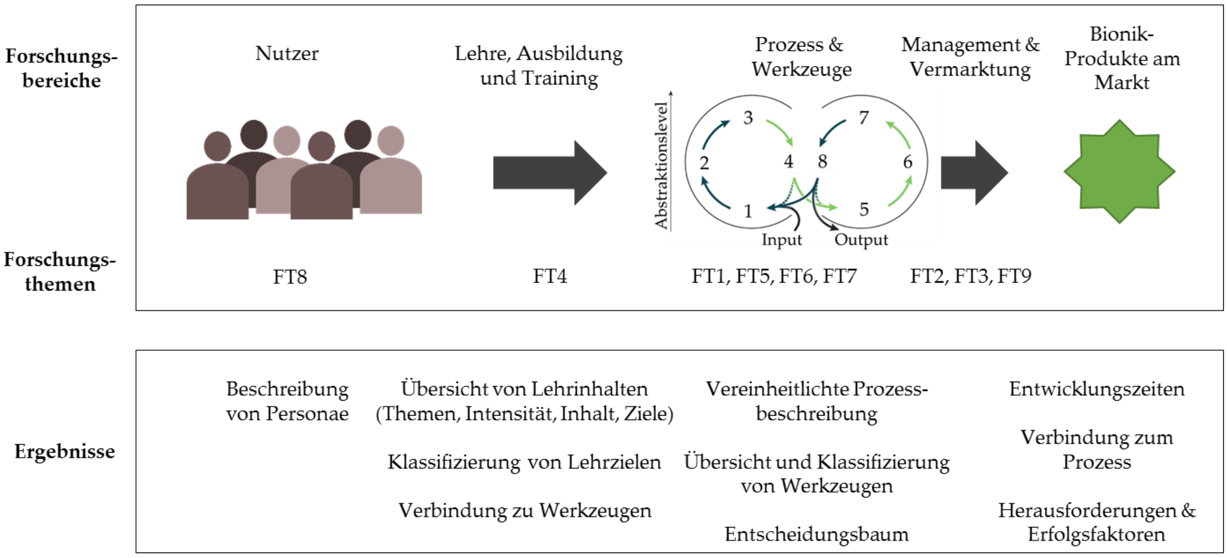

Abbildung 3: Zusammenfassung der Ergebnisse. 1-8 beschreiben die Schritte des problemgetriebenen Bionik-Prozesses nach Fayemi et al. (2017): 1: Problemanalyse, 2: Problemabstraktion, 3: Übertragung in die Biologie, 4: Suche biologischer Vorbilder, 5: Auswahl geeigneter Vorbilder, 6: Abstraktion der Biologie, 7: Übertragung in die Technik, 8: Anwendung und Tests; FT: Forschungsthema

4.1 Bionik im Entwicklungsprozess von Produkten und Innovation

Die systematische Einbindung der Bionik in den Entwicklungsprozess von Produkten umfasst zahlreiche Aspekte, was in Abbildung 1 dargestellt ist. Um diese Einbindung erfolgreich zu gestalten, gab es in den vergangenen Jahren verschiedene Ansätze (Gramann, 2004; Hollermann, 2012; ISO/TC 266, 2015; Jordan, 2010; Lindemann, 2009; Rosa et al., 2015; Stricker, 2006), welche die Grundlage geschaffen haben, damit sich die Bionik neben der Grundlagenforschung auch in Richtung der praktischen Anwendung entwickeln konnte.

Es gibt grundsätzlich zwei Möglichkeiten, wie Bionik in der Praxis zur Anwendung kommt: Zum einen kann sie ergänzend zur Entwicklungsarbeit eingesetzt werden, indem ihr Vorgehen in die klassische Arbeit integriert wird (Beismann, 2018; Lindemann, 2009). Dies kann beispielsweise dadurch passieren, dass sie in der Phase der Ideengenerierung als Kreativitätstechnik eingesetzt wird. Daneben kann die Bionik aber auch eigenständig als neuartiger Weg der Problemlösung genutzt werden, indem bewusst ein Projekt die Phasen der Bionik durchläuft und eine Lösung nach einem biologischen Vorbild entwickelt wird.

Die Existenz verschiedener Begriffe, Prozessbeschreibungen und Werkzeuge im Kontext der Bionik verdeutlicht eine erste Schwierigkeit der Bionik, die in ihrer Inter- und Transdisziplinarität[9] begründet ist. So leisten die verschiedensten Disziplinen einen Beitrag zur Bionik und ihren Prozessen, sodass Fachwissen, Sprache und Terminologie divers und nicht immer miteinander kompatibel sind. Dies bedeutet, dass beispielsweise methodische Ansätze, die der Bionik zu einer reproduzierbaren und skalierbaren Vorgehensweise verhelfen sollen (Goel et al., 2014), verschiedene Herangehensweisen, unterschiedliche Motivationen und Zielsetzungen sowie Bedeutungen haben. Dies ist für die Erstellung und Kommunikation einer einheitlichen Theorie der Bionik (Goel et al., 2014) hinderlich. Deshalb ist ein Kernziel der vorliegenden Arbeit die Zusammenstellung und Analyse von vorhandenem Wissen, um dadurch Ansatzpunkte für die Vereinheitlichung der Bionik zu identifizieren sowie einen Ausgangspunkt für die Zusammenführung dieser Wissenselemente zu schaffen.

4.1.1 Werkzeuge und Methoden

Für die Zusammenführung von vorhandenem Wissen wurden zunächst die verschiedenen Prozessbeschreibungen in eine vereinheitlichte Beschreibung für den problemgetriebenen Prozess der Bionik überführt (Fayemi et al., 2017). In einigen Beschreibungen der Bionik als Prozess fehlten bisher essenzielle Schritte, z. B. die Auswahl geeigneter Vorbilder aus der Biologie (Schritt 5). Daher wurden die Kernschritte verschiedener Beschreibungen ergänzt und in einer zusammengeführten Darstellung aufgegriffen. Dies diente dazu, ein vertieftes Verständnis für den Prozess der Bionik zu ermöglichen und damit zu einem gemeinsamen Verständnis, einer gemeinsamen Sprache und einer praxisorientierten Anwendung der Bionik beizutragen.

Neben der vereinheitlichten Prozessbeschreibung wurde die Einbindung von Werkzeugen und Methoden über den bisherigen Stand des Wissens erweitert (Goel et al., 2014; Hollermann, 2012). Dazu wurden 43 bereits entwickelte Werkzeuge und Methoden zusammengefasst und analysiert, um dieses vorhandene Wissen zukünftig vermehrt nutzen zu können.

Darüber hinaus wurden die analysierten Werkzeuge basierend auf den erzielten Ergebnissen aus den durchgeführten Workshops mit der vereinheitlichten Prozessbeschreibung verknüpft und so ein Entscheidungsbaum erstellt, der als methodische Vorgehensweise in der Praxis eingesetzt werden kann (Fayemi et al., 2017).

[9] Dieser Aspekt wird in Abschnitt 4.3 (S. 36) näher betrachtet.

Der Entscheidungsbaum wurde erstellt, indem die einzelnen Schritte der Prozessbeschreibung durch Entscheidungsfragen erweitert und mit Werkzeugen verknüpft wurden. Die Knotenpunkte in diesem Entscheidungsbaum wurden anhand der Bewertungskriterien aus der statistischen Analyse der Werkzeuge definiert oder basierten auf Charakteristika der Projekte, wie z. B. Nachhaltigkeitsaspekte. Der Nutzer wird durch Fragen im Entscheidungsbaum zu den jeweiligen Werkzeugen und Folgeschritten geleitet (Fayemi et al., 2017).

Die Analyse von Werkzeugen der Bionik ist herausfordernd, da es keine geeignete Bewertungsmethode aus der eigenen Disziplin gibt. Wenige der Entwickler haben ihre Werkzeuge in der praktischen Anwendung getestet. In der Regel gab es eine konkrete Aufgabenstellung, wie z. B. die Entwicklung einer Suchmaschine für biologische Fachliteratur (Kaiser et al., 2014), um den Zugang zum Wissen der Biologie zu ermöglichen und geeignete Vorbilder für Bionik zu identifizieren. Oder z. B. die Entwicklung eines Thesaurus, der die Kommunikation zwischen Biologie und Technik erleichtert (Nagel et al., 2010). Diese Aufgabenstellung wurde in den jeweiligen Arbeiten gelöst und das entsprechende Werkzeug entwickelt. Die durchgeführten Tests bezogen sich dann auf die Erfüllung der primären Aufgabe, eine Bewertung in der Anwendung fand in der Regel nur durch interne Fallstudien statt. Ausnahmen sind beispielsweise *AskNature* ("AskNature"), eine Datenbank, bei der sich leicht Nutzerdaten durch Cookies sammeln lassen. Oder auch die Werkzeuge *Four-Box-Method* und *T-Chart* von Helms und Goel, die ihre Werkzeuge in Arbeiten mit Studierenden evaluiert haben (Helms und Goel, 2014).

Zur allgemeinen und fachübergreifenden Bewertung von Werkzeugen wurden im Rahmen der vorliegenden Arbeit verschiedene Ansätze getestet, die aus dem Bereich Produktentwicklung und Marketing, Mathematik oder Informatik stammen, wie z. B. die kategorische Mehrkomponentenanalyse *CATPCA (categorical principle components analysis)*. Darüber hinaus zeigen Yargin et al. einen Ansatz aus der Softwareanalyse (Yargin et al., 2017). Trotzdem ist die einheitliche objektive Bewertung von Werkzeugen und eine statistisch signifikante Auswertung kaum realisierbar, da 1) die Nutzergruppen divers sind und damit 2) keine statistisch relevante Stichprobe von Nutzern existiert, die ausreichend in den verschiedenen Werkzeugen geschult sind, 3) es keine ausreichenden Daten über die Anwendung der Werkzeuge in der praktischen Anwendung gibt und 4) die Werkzeuge unterschiedliche Prozessschritte unterstützen und daher projektspezifisch eingesetzt würden.

Aus diesen Gründen wurde die beschriebene qualitative Klassifizierung gewählt und diese mit einer theoretischen Nutzeranalyse verknüpft. Weitere Arbeiten können darauf aufbauen und:

- das Feedback von Nutzern einholen und auswerten (Industrievertreter, Bionik-Experten),
- Interviews mit Entwicklern führen, um die Erweiterung und Vernetzung der Werkzeuge zu eruieren,
- die Klassifizierung der Werkzeuge erweitern, indem zusätzliche Variablen definiert werden,
- statistische Analysen einsetzen (Weiterentwicklung CATPCA-Daten) sowie
- die Klassifizierung der Werkzeuge und die Prozessbeschreibung auf Nutzer abstimmen.

Zusätzlich wurden die Werkzeuge entsprechend der Klassifizierung und Analyse den einzelnen Prozessschritten der Bionik zugeordnet. Dies ermöglicht zunächst eine bessere Bekanntheit vorhandener Werkzeuge und Methoden. Darüber hinaus fördern die Ergebnisse die Auswahl geeigneter Werkzeuge für Projekte und sie können helfen, den Entwicklungsprozess systematisch zu unterstützen. Das Ergebnis ist eine zunächst deskriptive Methodik, die zu einem Entscheidungsbaum zusammengeführt wurde (Fayemi et al., 2017). Dadurch leistet die Arbeit einen Beitrag dazu, um den Prozess der Bionik in der Praxis leichter anwenden zu können, indem Nutzer eine Vorgehensweise aufgezeigt bekommen, die sie als Leitfaden verwenden und individuell erweitern können. Ein Beispiel für eine solche erfolgreich abgeleitete Vorgehensweise „Bionik in Entwicklungsprozesse integrieren“ wird im Themenbereich der Strukturoptimierung in der Literatur beschrieben (Beismann, 2018). Darüber hinaus entwickelt der Verein Deutscher Ingenieure (VDI) eine neue Richtlinie, die sich mit der Bionik in der Produktentwicklung befasst.[10]

Rund 56% der analysierten Werkzeuge bauen auf den Ergebnissen vorheriger Prozessschritte auf, die die nachfolgenden Schritte des Prozesses beeinflussen. Bedenkt man, dass alle Werkzeuge unabhängig und z. T. in verschiedenen Disziplinen entwickelt wurden, wird deutlich, dass eine Weiterentwicklung der Werkzeuge deren Wirkmächtigkeit erhöhen könnte, wenn sie Ergebnisse und Arbeitsweise vernetzter Werkzeuge mit berücksichtigen würden. Dies würde eine enge Kooperation der Entwickler erfordern, wozu die vorliegende Arbeit ermutigt.

[10] Die konstituierende Sitzung dazu fand im Mai 2019 statt. Die Autorin der vorliegenden Arbeit hat daran teilgenommen.

Die vorgestellten Ergebnisse können in Zukunft mit neuen Werkzeugen erweitert werden. Mit zunehmender Anzahl von Produkten, die am Markt angekommen sind, nehmen darüber hinaus die Erfahrungen aus der Produktentwicklung zu und können ausgewertet werden. Auch kann erwartet werden, dass die Zahl von Anwendern und Nutzern der Methodik steigt. All diese Aspekte können weiterhin zur Verbesserung der Methodik beitragen.

4.1.2 Entscheidungsbaum

Der entwickelte Entscheidungsbaum von Fayemi et al. (2017) kann Nutzern branchenübergreifend als Leitfaden dienen, um Werkzeuge und Methoden für den Prozess der Bionik einzusetzen. Die Struktur ist so gewählt, dass an den Nutzer keine speziellen Anforderungen gestellt werden, da an einigen Knotenpunkten das Vorwissen der Nutzer abfragt und berücksichtigt wird. Allerdings muss der Nutzer eine Offenheit und Bereitwilligkeit für die Auseinandersetzung mit den verschiedenen Werkzeugen mitbringen. Somit richtet sich der Entscheidungsbaum auch an Nutzer, die z. B. in KMU arbeiten. Häufig besitzen KMU keine eigenen Innovationsabteilungen, sodass der Einsatz von Bionik in den Arbeitsbereich der Entwickler fällt. Eine systematische Vorgehensweise kann dabei den Einsatz von Bionik fördern. Dabei benötigtes Fachwissen kann durch externe Expertise hinzugeholt werden.

Die Ergebnisse über den Weg von Bionik-Konzepten bis zur Kommerzialisierung von Produkten lassen sich weiter ausarbeiten und mit dem Entscheidungsbaum verknüpfen, um ihn über Schritt 8 hinweg weiterzuentwickeln. Auch können die Phasen des konvergenten und divergenten Denkens[11] (Funke, 2000) während des Prozesses stärker differenziert und strukturiert werden.

Um die Einsatzfähigkeit des Entscheidungsbaums in der Praxis zu prüfen, kann die Forschungsarbeit fortgesetzt werden. In diesen weiteren Arbeiten kann der Entscheidungsbaum zunächst durch konkrete Praxisbeispiele getestet und angepasst werden. Nutzerdaten und Assessments können die Praxistauglichkeit überprüfen und die Bedeutung für die Wirtschaft messbar machen. Darüber hinaus kann er auch in der Arbeit mit Studierenden zum Einsatz kommen, um seine Allgemeingültigkeit für verschiedene Nutzergruppen zu überprüfen und um ihn dann ggf. anzupassen.

[11] Konvergentes Denken beschreibt die zielgerichtete Arbeit auf „die eine“ Lösung hin, wobei unter divergentem Denken die kreative Ideengenerierung durch Assoziationen und Perspektivenwechsel verstanden wird, die zu möglichst vielen Lösungsideen führt (nach Guilford (1967) in Funke, 2000).

Geht man davon aus, dass Bionik theoretisch jegliches praktisches Problem bearbeiten kann, dann stellt sich die Frage, ob der Prozess bisher allgemeingültig genug beschrieben ist. Wie bereits erwähnt kann die Bionik auf verschiedenen Ebenen der Innovation eingesetzt werden und die Ergebnisse können inkrementelle oder radikale Verbesserungen bewirken. Dies wurde auf Ebene der Produktinnovation bereits gezeigt, wie z. B. beim Selbstreinigungseffekt der Lotus-Pflanze als eine radikale Innovation (Barthlott und Neinhuis, 1997). Hinsichtlich der erwähnten Annahme muss sich der Prozess der Bionik aber auch auf Prozesse, Organisationen und Systeme sowie die Gesellschaft im Allgemeinen übertragen lassen. Die Ergebnisse der vorliegenden Arbeit haben dazu einen ersten Beitrag geleistet, indem eine allgemeine Prozessbeschreibung erstellt wurde. Der Prozess lässt sich aber weiter erforschen, definieren und mit anderen Methoden kombinieren. Dabei können die Ergebnisse beispielsweise mit der Anwendung der Bionik auf der Systemebene, z. B. in der Wirtschaftsbionik (Ferdinand et al., 2012), verknüpft werden. Dabei werden Prinzipien der Natur, wie Resilienz oder Adaptivität, auf Unternehmen und Branchen übertragen. Erste Werkzeuge aus diesem Bereich wurden bereits entwickelt, u. a. für Geschäftsmodelle ("ResilieNtWEB"). Die dafür zu leistende Forschungsarbeit bedarf der interdisziplinären Zusammenarbeit und sie ist eng verknüpft mit dem lösungsbasierten Ansatz der Bionik, was in Kapitel 5 näher erläutert wird.

Darüber hinaus kann die internationale Vorarbeit für ein einheitliches Verständnis der Bionik erweitert werden (ISO/TC 266, 2015), indem für die Bionik als strukturierte Innovationsmethodik ein Bezug zu Design- und Managementmethoden hergestellt wird.

4.2 Design- und Projektmanagement

Die Bionik hat bekannte Überschneidungen mit anderen Innovationsmethoden, wie z. B. der Theorie des erfinderischen Problemlösens *TRIZ* (Herb et al., 2000; Vincent und Cavallucci, 2018; Vincent et al., 2006; Vincent und Mann, 2002). Daraus haben sich bereits eigene Vorgehensweisen für die Bionik abgeleitet, wie z. B. *BioTRIZ* (Bogatyrev und Bogatyreva, 2014; Vincent et al., 2006). Daneben lassen sich für Bionik auch Verbindungen herstellen mit weiteren Problemlösungsstrategien, wie *Design Thinking* (Buchanan, 1992; Plattner et al., 2011), oder zu systemischen Lösungsansätzen, wie z. B. *Circular Economy* (Geissdoerfer et al., 2017; Kirchherr et al., 2017). So haben einige Arbeiten bereits analysiert, welche Ähnlichkeiten und Überschneidungen nachhaltigkeitsorientierte Konzepte mit der Bionik haben (de Pauw et al., 2010; Tempelman et al., 2015). Allerdings gibt es noch keine Arbeiten darüber, wie sich Bionik-Projekte allgemein erfolgreich managen lassen.

Die vorliegende Arbeit befasst sich deshalb auch mit den grundsätzlichen Schwierigkeiten der Innovation und dem Innovationsprozess der Bionik, wie sie z. B. im „*Valley of death*" beschrieben werden (Bhushan, 2015). So konnte gezeigt werden, dass bionische Innovationen Entwicklungszeiten von durchschnittlich 6-9 Jahren aufweisen. Im Rahmen der Forschungsarbeit stellte sich daher die Frage, ob Bionik-Projekte durch ein spezielles Projektmanagement zu schnelleren Erfolgen gebracht werden können. Eine Bachelorarbeit befasste sich mit dem Einsatz agiler Projektmanagementmethoden in einer bionischen Entwicklung (Weinzierl, 2018). Die Ergebnisse der Arbeit unterliegen der Geheimhaltung, allerdings konnten bereits erste Einblicke gewonnen werden, wie Bionik mit Projekt- und Innovationsmanagement–Methoden verknüpft werden kann. So können beispielsweise die aus dem *Design Thinking* bekannten Phasen aus kreativem und lösungsorientiertem Arbeiten auch in der Bionik bewusster eingesetzt werden und damit in zeitlich kurzen Entwicklungsphasen erste messbare Zwischenergebnisse erzielen.

4.3 Multi-, Inter- und Transdisziplinarität im Prozess der Bionik

Im Prozess der Bionik arbeiten verschiedene Disziplinen zusammen, was allgemein als die Verbindung von Biologie (Naturwissenschaften) und Technik (Ingenieurwissenschaften) bezeichnet wird. Die Bionik ist damit per Definition interdisziplinär, und das aus der Zusammenarbeit resultierende Wissen ist ein gemeinsames Produkt, das sich nicht mehr einer der Einzeldisziplinen zuordnen lässt. Damit lassen sich komplexere Problemstellungen bearbeiten, was wiederum eine einheitliche Vorgehensweise erfordert. Die vorliegende Arbeit präsentiert dafür die vereinheitlichte Prozessbeschreibung, die Übersicht vorhandener Werkzeuge, den Entscheidungsbaum sowie die wesentlichen Inhalte für eine effektive Lehre und Ausbildung. Darüber hinaus können die einzelnen Disziplinen einen Beitrag zur Bionik leisten, indem sie wie bereits erwähnt z. B. Werkzeuge und Methoden entwickeln und so zum multidisziplinären Charakter der Bionik beitragen. Dies führte bisher zu den verschiedenen diversen Wissenseinheiten, die in der vorliegenden Arbeit z. T. zusammengeführt werden. Damit wird ein Beitrag zur Interdisziplinarität der Bionik geleistet, die auf eine gemeinsame Terminologie, Standards und Praxen angewiesen ist.

Die Rolle einzelner Akteure in Bionik-Projekten ist ebenfalls ein wichtiger Aspekt der interdisziplinären Zusammenarbeit. Bisher wird insbesondere die Rolle von Biologen erforscht und betont (Graeff et al., 2018; Snell-Rood, 2016). Darüber hinaus gibt es in einem Bionik-Team aber neben den disziplinären Rollen „Biologe und Ingenieur" (ISO/TC 266, 2015) auch interdisziplinäre Aufgaben, die mit den kreativen und kognitiven Aspekten im Bionik-Prozess verknüpft sind. Die Forschung daran wird aufbauend auf den Ergebnissen der vorliegenden Arbeit bearbeitet und kann zur Transformation der Bionik zu einer reproduzierbaren Methodik beitragen, was Goel et al. (2014) wie bereits erwähnt als aktuelle Herausforderung ansehen.

Die Bionik besitzt gerade im Hinblick auf ihre Anwendungspotenziale auch transdisziplinäre Aspekte, indem nicht-akademische Akteure in den Prozess eingebunden sind. Löst man die Bionik von ihrem Charakter als Wissenschaftsdisziplin und betrachtet sie als eine Innovationsmethodik für Industrie und gesellschaftliche Herausforderungen, dann ist die Beteiligung von Akteuren aus Wirtschaft, Politik und Gesellschaft essenziell. Die vorliegende Arbeit hat sich auf Nutzer aus der Wirtschaft fokussiert und damit eine Verbindung zur Transdisziplinarität der Bionik aufgezeigt. Allerdings bedarf es der stärkeren Einbindung von entsprechenden Akteuren in den Weiterentwicklungsprozess der Bionik hin zu einem Ansatz, der zur Lösung der gesellschaftlichen Probleme unserer Zeit beitragen kann. Dafür sollte der Einfluss von nicht-akademischem Expertenwissen zur Bionik erhöht werden. Dies kann allerdings schwierig sein, wenn notwendige Akteure die Bedeutung der Bionik aufgrund verschiedener Hemmnisse bisher nicht einschätzen können. Abbildung 4 verdeutlicht, welche Bekanntheit Bionik in Unternehmen haben kann und welche Gründe ihre praktische Anwendung verhindern können.

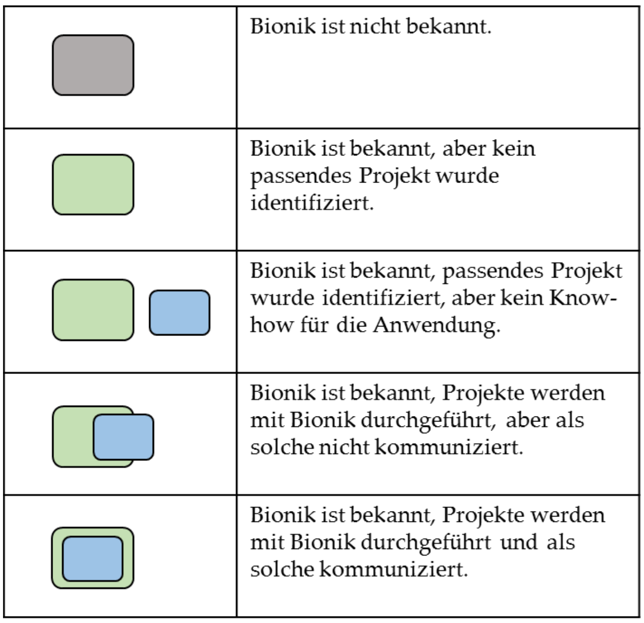

Abbildung 4: Bekanntheit und Einsatz von Bionik in Unternehmen.

Allerdings ist das Interesse der Industrie an Bionik durchaus vorhanden, was u. a. die Ergebnisse eines Projektes während der bisherigen Forschungsarbeit zeigen. So kamen 72% der 267 Teilnehmer von Informationsveranstaltungen zur Bionik aus der Wirtschaft und 16% aus der Wissenschaft (Ergebnisse des Projektes ImB[12], unveröffentlicht). Das Projekt hat gezeigt, dass die Bewusstseinsbildung für Bionik in der Industrie sowie der Wissenstransfer aus der Forschung essenziell sind, um den Einsatz der Bionik in Unternehmen zu stärken.

Um in Zukunft auch gesellschaftliche Herausforderungen durch Bionik bearbeiten zu können, bedarf es der umfassenden Betrachtung und Reflexion der Bionik.

4.4 Die Theorie der Bionik

Der Bionik wird das Potenzial für einen bedeutenden wissenschaftlichen, gesellschaftlichen und wirtschaftlichen Beitrag zugesprochen (Lepora et al., 2013). Die Frage dabei ist, wie die Bionik dieses Potenzial entfaltet und welche Rolle sie dabei einnimmt.

Die Ergebnisse der vorliegenden Arbeit haben zum Verständnis der Bionik als eine *Disziplin* beigetragen, welche sich durch fünf Charakteristika beschreiben lässt (Stichweh, 2013): 1) es besteht eine wissenschaftliche Gemeinschaft (*scientific community*), 2) es gibt eine Wissensbasis, die in Lehrbüchern repräsentiert ist und sich grundsätzlich lehren lässt, 3) es gibt eine „Mehrzahl je gegenwärtig problematischer Fragstellungen“, 4) es gibt diverse Forschungsmethoden und „paradigmatische Problemlösungen“ und 5) es gibt eine Disziplinen spezifische Karrierestruktur. So verfügt die Bionik zwar bereits über eine *scientific community* und über umfangreiches Wissen (Lepora et al., 2013). Dieses Wissen befindet sich allerdings weniger in Lehrbüchern und auch die grundsätzliche Lehrbarkeit der Inhalte ist bisher divers. Die Ausbildung der nächsten Generation ist aber für das Verständnis der Bionik als Disziplin wichtig und auch Goel et al. (2014) erwähnen dies als eine der großen Herausforderungen für die Bionik. Die notwendigen Faktoren für eine erfolgreiche Ausbildung in der Bionik waren lange unklar (Yen et al., 2014) und die vorliegende Arbeit hat an diesen Punkten angesetzt. Mit den beschriebenen Lehr- und Ausbildungsangeboten gibt es erste Ansätze für eine „disziplinenspezifische Karrierestruktur“ (Stichweh, 2013), allerdings ist diese eher bereichsübergreifend und Teil vorhandener anderer Disziplinen. Basierend auf der Analyse der Lehrinhalte und - ziele kann in Zukunft die Lehrbarkeit der Bionik unterstützt werden. Damit lassen sich auch die Lehrangebote der Autorin dieser Arbeit überarbeiten und in der Praxis in ihrer Wirksamkeit testen.

[12] ImB – Innovativ mit Bionik! Projektnummer: J00332, Programm „Ziel Europäische territoriale Zusammenarbeit“ Deutschland/Bayern - Österreich 2007-2013

Des Weiteren sollte in Zukunft geklärt werden, wie sich gegenwärtige und zukünftige Fragestellungen, die die Bionik lösen kann, definieren lassen und welches „Set von Forschungsmethoden und paradigmatischen Problemlösungen“ (Stichweh, 2013) die Bionik bereithält. Dazu zählen beispielsweise auch geeignete Assessments.

Abbildung 5 verdeutlicht einige Aspekte von benötigten Assessments für Problemstellungen und Ergebnisse des Bionik-Prozesses.

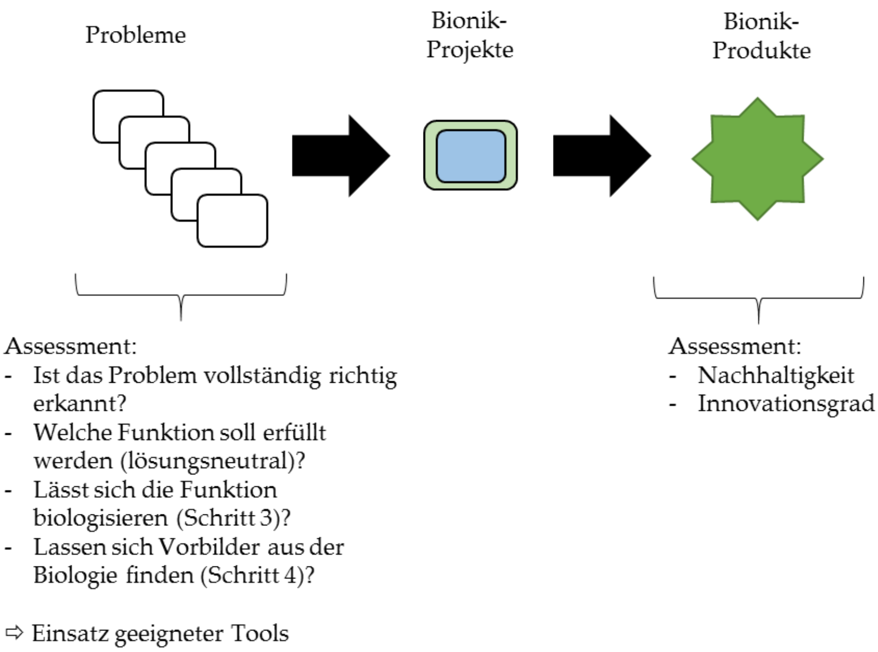

Abbildung 5: Assessment von Bionik-Projekten.

Das Assessment von Bionik-Produkten wird bereits erforscht. So konnte gezeigt werden, wie sich Bionik-Produkte im Hinblick auf ihren Beitrag zur Nachhaltigkeit hin untersuchen, bewerten und klassifizieren lassen (Antony et al., 2016, 2014; Speck et al., 2017). Und in Bezug auf den Innovationsgrad wird aktuell ein methodisches Vorgehen im Rahmen des ISO TC 266 erarbeitet.

Für das Assessment von Problemen gibt es bisher keine Vorgehensweise. Die weitere Forschung kann sich daher im Vorfeld von Projekten mit einer geeigneten Problemanalyse befassen, um zu klären, welche Probleme sich durch Bionik lösen lassen. So können in Zukunft erfolgreiche Fälle untersucht sowie Branchen, Fragestellungen und Themenbereiche abgeleitet werden, die sich durch Bionik bearbeiten lassen.

5. Ausblick

Die Bionik gilt in der Produktentwicklung als etabliert (Ferdinand et al., 2012), allerdings muss sie sich als wissenschaftliche Disziplin noch weiterentwickeln (Lenau, T. A., 2009). Die vorliegende Arbeit hat einen Beitrag zu dieser systematischen Weiterentwicklung geleistet und aufgezeigt, dass weitere Forschung notwendig ist, um den Weg der Bionik hin zu einer robusten Methodik zu gestalten.

Die Forschung der vorliegenden Arbeit konzentriert sich auf den problemgetriebenen Prozess der Bionik. In Zukunft könnte aber auch der lösungsbasierte Ansatz stärker erforscht werden. Dieser Ansatz ist bisher eher mit einer Zufallsentdeckung gleichzusetzen (Jacobs et al., 2014), er könnte aber ebenso systematisch aufgearbeitet werden. Dadurch könnte er insbesondere zum erwähnten Assessment von Problemstellungen im unternehmerischen Umfeld sowie zu einem verstärkten Einsatz in der Industrie beitragen. Dabei würden vor allem die folgenden Forschungsfragen interessant sein:

a) Wie lassen sich die zugrundeliegenden Prinzipien von Phänomenen der Biologie erkennen und einheitlich beschreiben?
b) Wie kann Grundlagenwissen aus der Biologie systematisch für die Bionik aufbereitet und im Prozess eingesetzt werden?
c) Wie lassen sich Phänomene der Biologie als *Lösung* für eine technische Anwendung identifizieren?
d) Wie lässt sich der lösungsbasierte Prozess der Bionik systematisch beschreiben?
e) Wie lassen sich der problemgetriebene und der lösungsbasierte Ansatz der Bionik methodisch verbinden?
f) Welche Werkzeuge können für den lösungsbasierten Ansatz eingesetzt werden?

g) Was wäre eine geeignete BOS[13] für Bionik-Phänomene zur Erkennung von Anwendungsfeldern in der Industrie?
h) Wie lassen sich Firmen geeignet ansprechen?

Einige dieser Fragen sind in den letzten Jahren bereits formuliert (Fu et al., 2014) und bearbeitet worden (Badarnah und Kadri, 2015; Kruiper et al., 2017; Nagel et al., 2010; Vincent, 2014). Allerdings stammen die Ergebnisse auch hier aus verschiedenen Disziplinen und sie verfolgen unterschiedliche Ziele. Eine einheitliche Betrachtung und Bearbeitung dieser Fragen sowie die Entwicklung von Assessments können in Zukunft zu einer skalierbaren Methodik für Bionik beitragen, wie sie Goel et al. (2014) fordern.

Neben der Fokussierung der Forschung auf die Prozesse der Bionik mit den aufgezeigten Facetten lässt sich die Bionik in den Kontext des globalen Wandels und der Nachhaltigkeit stellen. So kann ein Ziel der Bionik der aktive Beitrag zum Erhalt der Biodiversität und zu einer umweltverträglichen Produktion sein sowie zu einem grundlegenden Umdenken der Produktentwicklung, des Gestaltens von Prozessen und des Konsums (vgl. Niebaum und Seitz, 2017). Produkte und Dienstleistungen lassen sich neu denken, indem es nicht alleine darum geht, z. B. Einzelfunktionen eines Automobils zu optimieren, sondern Mobilität neu zu denken. Die Bionik kann damit helfen, völlig neue Denk- und Lösungsansätze zu generieren (vgl. Lenau et al., 2018a). Biologisierung von Technik und Wirtschaft[14] ist ein gegenwärtiger Trend und es gilt, die Bionik in diesem Kontext zu positionieren.

In diesem Zusammenhang soll in Zukunft zum einen der Beitrag der Bionik zum technischen Umweltschutz erforscht werden. Darüber hinaus soll das Potenzial der Bionik für einen Beitrag zu den Nachhaltigkeitszielen der Vereinten Nationen[15] erforscht werden (Gebeshuber et al., 2009), indem die Bionik im Rahmen der sozial-ökologischen Forschung die Gestaltung gesellschaftlicher Transformationsprozesse mit bestimmt. Damit könnte die Bionik langfristig zur Lösung komplexer Herausforderungen dieser Zeit beitragen.

Die erwähnten offenen Forschungsansätze können einen messbaren Beitrag leisten, um die Bionik stärker in der Anwendung zu platzieren und damit langfristig den globalen Wandel mitzugestalten.

[13] Siehe Abschnitt 1.1, S. 5.
[14] Die Fraunhofer Gesellschaft hat diesen Begriff in ihrem Grundlagenpapier geprägt ("Biologisierung").
[15] Siehe https://sustainabledevelopment.un.org [zugegriffen am 25.06.2019].

6. Zusammenfassung

6.1 Zusammenfassung in Deutsch

Das Lösen von technischen oder praktischen Problemen stellt in allen Bereichen der Gesellschaft eine Herausforderung dar. Die Bionik kann ein Weg der Problemlösung sein, indem Wissen aus der Biologie abstrahiert und auf das Problem übertragen wird. Bionik ist eine wachsende Wissenschaftsdisziplin, die in den letzten Jahrzehnten zu bedeutenden Entwicklungen geführt hat. Grundsätzlich kann der Prozess der Bionik auf zwei Arten ablaufen: zum einen lösungsbasiert, wobei die Naturbeobachtung der Ausgangspunkt ist für eine Technikanwendung, oder problemgetrieben, wobei man für ein technisches Problem gezielt in der Natur nach einem geeigneten Vorbild für die Lösung sucht. Das Potenzial der Bionik für Innovation basiert u. a. auf der Biodiversität mit Millionen verschiedener Arten und wird daher als immens eingestuft. Zudem könnte sie eine Schlüsselfunktion in der unternehmerischen Entwicklungsarbeit einnehmen. Damit kann die Bionik in Wissenschaft, Wirtschaft, Gesellschaft und für den Umweltschutz einen bedeutenden Beitrag leisten. Allerdings ist der Prozess des Wissenstransfers aus der Biologie in die Praxis komplex und erfordert inter- und transdisziplinäre Zusammenarbeit. Auch Nutzer sehen sich spezifischen Herausforderungen gegenüber. Darüber hinaus steht die Bionik vor der Herausforderung, ihr Potenzial in eine skalierbare und reproduzierbare Methodik umzuwandeln.

In der vorliegenden Arbeit wurde der problemgtriebene Prozess der Bionik erforscht und vorhandene Prozessbeschreibungen in einer vereinheitlichten Version zusammengefasst. Diese Prozessbeschreibung umfasst acht definierte Schritte, aus denen ein Entscheidungsbaum abgeleitet wurde, der in der Praxis angewendet werden kann. Vorhandene Werkzeuge der Bionik können eingesetzt werden, um Herausforderungen während des Prozesses zu überwinden, und sie können die einzelnen Schritte unterstützen. Die vorliegende Arbeit stellt 43 Werkzeuge in einer Übersicht vor und hat sie qualitativ analysiert. Diese Klassifizierung zeigt, dass einzelne Prozessschritte gut und andere Schritte bisher nicht durch Werkzeuge unterstützt werden können und dass eine Weiterentwicklung des methodischen Vorgehens der Bionik erforderlich ist. Im Hinblick auf die Diskrepanz zwischen dem technischen Potenzial der Bionik und vorhandener marktfähiger Produkte werden Erfolgsfaktoren für bionische Entwicklungen bis hin zur Kommerzialisierung präsentiert. Der Entwicklungsprozess der Bionik wird mit dem klassischen Innovationsprozess verknüpft und spezifische Herausforderungen abgeleitet.

Darüber hinaus kann die Bionik als eine Denkweise für Kreativität und als eine Methode für den effektiven Wissenstransfer zwischen Disziplinen verstanden werden. Damit erreicht die Bionik Nutzer im akademischen und nicht-akademischen Umfeld, weshalb ein vertieftes Verständnis über die Lehre dieser Methodik notwendig ist. Die vorliegende Arbeit präsentiert eine Auswahl aktueller Lehrinhalte in Programmen des öffentlichen und privaten Sektors und stellt Empfehlungen für die Gestaltung von zukünftigen Lehrinhalten vor. Durch ein besseres Verständnis für die Nutzer der Bionik und deren Bedürfnisse wird die Möglichkeit zur Verbesserung des Prozesses eröffnet. Die Ergebnisse der Arbeit sollen langfristig die Anzahl erfolgreicher bionischer Entwicklungen und Innovationen erhöhen. Außerdem soll die Prozessbeschreibung und Weiterentwicklung der Bionik als Methode zukünftig zur Lösung komplexer lebensweltlicher Probleme in der Gesellschaft beitragen.

6.2 Zusammenfassung in Englisch

Solving technical and practical problems is a challenge in all areas of society. Biomimetics can be a problem solving strategy by abstracting and transferring knowledge from biology to the problem. Biomimetics is an emerging scientific discipline and has led to significant concepts over the past decades. In general, the process of biomimetics can be performed in two ways: on the one hand, the solution-based approach, which is based on a discovery in nature that could serve as a model for a technological application. On the other hand, the problem-driven approach, where one searches for an explicit model in nature that has solved a technological problem. The potential of biomimetics for innovation, amongst others, is based on the biodiversity of millions of species and it is considered to be immense. Additionally, biomimetics could function as a key process in businesses. As such, biomimetics can have a significant scientific, economic, societal, and ecological impact. However, the process of the knowledge transfer from biology to practice is complex and requires inter- and transdisciplinary cooperation. Also practitioners face specific challenges. In addition, biomimetics needs to be transformed into a scalable and repeatable methodology.

The dissertation at hand worked on the problem-driven process of biomimetics and unified existing process descriptions. This unified process description consists of eight defined steps,

which were used to create a decision tree that can be used in practice. Existing tools from biomimetics can be used to overcome challenges during the process and they can facilitate the respective steps. This dissertation presents an overview of 43 tools and their qualitative analysis. The classification of these tools shows that certain steps of the process and their challenges are well addressed by the tools, while other steps are not. Additionally, the further development of the methodological approach of biomimetics is suggested. With regard to the discrepancy between the potential of biomimetics and existing market ready products the dissertation presents success factors for biomimetic developments, from the design process to the commercialization process. The development process of biomimetics is linked to the traditional innovation process and specific challenge are deducted.

Biomimetics can be understood as a mindset for creative thinking and as a methodology for an effective knowledge transfer between disciplines. As such it is relevant to practitioners in academic and non-academic fields of application. Therefore, a deeper understanding of teaching and training the methodology is important. The dissertation at hand presents a set of current learning objectives from public and private programs and gives recommendations for the design of future curricula. Through a deeper understanding for users of biomimetics and their needs the dissertation offers chances to improve its overall process.

The results of the dissertation shall contribute to the increase of biomimetic developments and innovation in the long-term. Additionally the process description and further improvements of biomimetics as a methodology shall contribute to solving complex societal challenges in the future.

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Anhang

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Biomimetics and its tools

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Biomimetics, as the transfer of strategies from biology to technology, is an emerging research area and has led to significant concepts over the past decades. The development of such concepts is described by the process of biomimetics, encompassing several steps. In Practice, beneficiaries of the process face challenges. Therefore, to overcome challenges and to facilitate the steps, tools have been developed in various areas, such as engineering, computing and design. However, these tools are not widely used yet. This paper presents an overview and a classification study of more than 40 tools with qualitative criteria. The criteria included, for example, the year of development, the accessibility of tools, the facilitated steps of the process or their contribution to sustainability. The classification shows that certain steps of the process and their challenges are well addressed by the tools, while other steps are not. The presented results contribute to the proposal of an improvement of the state of the art, and they build the foundation for future theoretical and practical analyses. These findings could contribute to increasing the implementation of biomimetics in various disciplines in the long term.

1. Introduction

Biomimetics applies principles and strategies from biological systems to engineering and technological products, processes and design in general. The potential of biomimetics is considered to be boundless,[1] and its significant scientific, societal and economic impacts will have benefits to the quality of life.[2] The rate of research publications on biomimetics has been increasing over the past years and has reached nearly 3000 papers per year, indicating that biomimetics is becoming a dominant paradigm for various technological disciplines, such as robotics and material sciences.[2] On the other hand, the number of commercially available biomimetic products is rather low (of 303 biomimetic cases, 28% are commercially available, 60% are in development, 8% are concepts and 2% are discontinued).[3]

1.1 Challenges for biomimetics in practice

According to Jacobs *et al.*,[3] some of the reasons which account for the small number of biomimetic products on the market is the lack of a clear method,[4] the difficulties of interdisciplinary work and the complexity of biology as a model. In line with these aspects, studies on teaching students in biomimetics have shown key challenges with the process – that is, communication across discipline boundaries, analysis of problems to solve and identification and understanding of biological systems.[5,6] Obviously, the process of biomimetics reveals gaps and challenges in Practice (Figure 1). Practice is referenced in this paper as the use of biomimetics for product development and idea generation, focused on the industrial context. In order to generate appropriate biomimetic design concepts with a potential for commercialisation, these gaps need to be overcome.

Significant research has been carried out to facilitate the systematic transfer of biological knowledge to technology and to present methods (e.g. Badarnah and Kadri[7]) to create tools which will ultimately facilitate the biomimetic process.[8] These tools can then be used in Practice as described earlier. Tools for biomimetics are referenced in this paper as means to be used in performing or supporting the biomimetic process or parts thereof. A method is referred to in the following as a way of accomplishing a task during the process of biomimetics – for example, describing biological systems (for instance, with the Four-Box method[9]) or analogy mapping of biological and technological systems (for instance, with the T-chart[9]). The process of biomimetics is described as a series of

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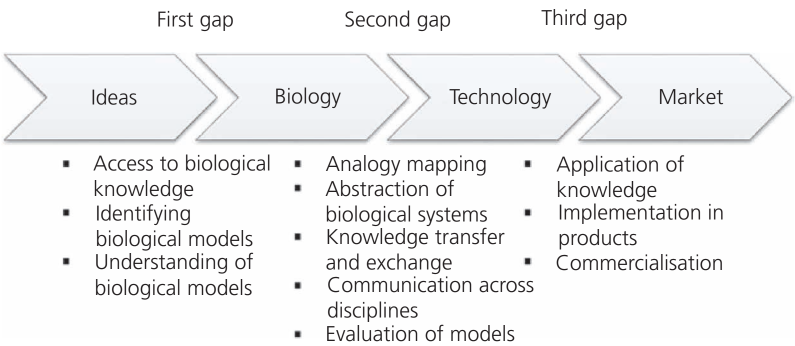

Figure 1. Gaps in the biomimetic design process and their underlying challenges[3,5,6]

steps – that is, actions, tasks and operations – leading to a biologically inspired design. If this design fulfils the three criteria for the definition of a biomimetic product[10] (which are (*a*) function analysis of a biological system, (*b*) abstraction from the system to a model and (*c*) transfer and application without using the biological system), it is considered not only to be biologically inspired, but also to be biomimetic. Different overall process descriptions of biomimetics which describe the phases of the process in Practice – for example, BioGen[7] or the Biomimicry DesignLens[11] (see also Fu *et al.*[1]) – are not included in the overview. It should be clarified that several publications exist which describe the implementation of biological principles, patterns or systems in technology – for example, Arzt,[12] Meyers *et al.*,[13] Naleway *et al.*,[14] Wegst *et al.*,[15] Barthelat[16,17] and Chen *et al.*[18] These publications certainly describe the process of applying biomimetics, but they rather differ from what the authors consider a tool, as they address a specific topic and not the process of biomimetics in general. This means that these processes can be used for a specific goal, but they do not describe a mean which facilitates the problem-driven approach to any possible problem. In this paper, a tool is clearly to be distinguished from a general biomimetic practice, which can be, for example, a field of research or development in the context of biomimetics. A tool is something differentiated with variables v1 and v2 (see Section 2.2) and is used in performing the different steps and underlying tasks of the biomimetic process in general. A tool also enables users to overcome the challenges that they face during the process (see Figure 1). For instance, AskNature[19,20] is a tool which overcomes the first gap of the process by offering a database for identifying biological models. In contrast, the description of, for example, next-generation materials[16] is not considered to be a tool, as it does not facilitate the process of biomimetics for any given problem. It is rather a presentation of biological knowledge useful for biomimetic developments, which is of value for sure in solving engineering problems in the context of materials. But if what is aimed is, for example, opening and closing mechanisms in nature, such source of information does not help to identify biological models for the given problem. In order to identify tools in the context of this paper, the distinction has been made as described. The authors are aware that there is literature and research going on which offer valuable knowledge on biomimetics. Furthermore, the field of biomimetics and its community is very broad and many actors are involved in the topic.[2,21,22] The aim of this paper is to focus on tools in particular; therefore, any research which did not fit the earlier mentioned definition is not considered.

Most of the existing tools have been described in the scientific literature, but were not widely used in the design of the 303 cases included in the BioM database.[3] Furthermore, as the research community is fragmented and involves many disciplines,[2,22] the development of these tools originates from different communities (such as the fields of scientific biomimetics, mechanical engineering, design, architecture, sustainability, creativity and innovation) with diverse areas of interest, research priorities and knowledge transfer practices. Although this diversity of disciplines contributes to the potential of biomimetics as an inter- and transdisciplinary approach, the knowledge and research findings are dispersed throughout academic, patent and popular literature.

Several notable publications have already summarised a subset of tools (e.g. Fu *et al.*,[1] Vincent *et al.*,[4] Stone *et al.*,[22] Glier *et al.*,[23] Goel *et al.*,[24] Nagel and Stone[25]), reviewed biomimetics for different users – that is, the scientific community[2]– carried out analytical studies with students (e.g. Helms *et al.*,[5] Yen *et al.*[6]) or provided case studies of existing products.[3] But so far, no general overview of existing tools from the different disciplines and communities exists. Additionally, little work has focused on theoretical analysis of tools (see Fu *et al.*,[1] Fayemi *et al.*[26]), and the development of highly effective tools which assist designers is emphasized.[27] It is therefore one aim of the present paper to give an overview of more than 40 existing tools which have been developed to facilitate and support biomimetics.

Furthermore, the results of a qualitative classification analysis are presented. The authors consider such a classification a way to gain insight about reasons for the lack of broad access. One reason for this lack could be the mere absence of knowledge about existing tools, indicating a communication gap between research and development. Another reason could be the lack of training and dissemination once tools are known. If one considers the various beneficiaries of biomimetics, it is almost impossible to train each of them in specific tools by the developers themselves. And one could assume that people interested in the topic might not have the skills necessary to access the scientific literature fully. Therefore, an overview of tools combined with a first approach of classifying and analysing them as a contribution to overcome the earlier mentioned gaps is highly needed. The presented theoretical analysis is an exploratory classification of existing tools. It does not test a specific hypothesis; instead, the aim is to use the data to build the foundation for further investigation and to establish hypotheses. This is a work in progress, and it will be combined with practical and further theoretical analyses. The authors also aim to clarify the beneficiaries of biomimetics. In general, biomimetics can be used in both the academia and industry, and the knowledge transfer from the academic field to the industrial application is key to foster success stories. Little research has focused on an audience analysis of biomimetics to identify differences in teaching and training methods. Furthermore, the development of tools did not differentiate potential users – that is, to raise the question of whether students might need tools other than those used by the designers from the industry. The authors consider this a necessary field of research, which is ongoing, but the presented analysis of tools may help to identify tools specific for certain target groups and how they can use appropriate tools for their own projects. The results presented are considered to be a state of the art of the existing tools, which will evolve in the future by including further and upcoming new tools.

2. Methods

2.1 Identification of existing tools

To identify existing tools of biomimetics, a literature review was carried out. A variety of search terms, including ‘biomimetics’, ‘biomimicry, ‘bioinspiration’, ‘biologically inspired design’ and ‘bionics’, in combination with the search term ‘tool’, were used to screen the literature. The use of general Web-based resources for journals and conferences were not helpful for several reasons.

- The tools of interest derive from several disciplines; therefore, diverse operational terms are used which scatter the literature.
- So far, no commonly used or standard keywords exist for tools in particular to enable the identification of appropriate literature.
- Therefore, although several search terms were tested, the results of a text-based search were not satisfactory – that is, known literature about tools was not discovered.
- Some tools are not described in the scientific literature.

In order to identify as many tools as possible, most of the tools were gathered by hand by using the snowball principle. The focus of this study was the identification of tools that specifically address the process of biomimetics and not, for instance, other creativity tools which could be used for the process of biomimetics as well, but which were originally developed for other purposes. As biomimetics spans several fields of application, the authors did not narrow down the search by discipline from which the tools were derived or for which field of application their use was intended. Therefore, the identified tools and methods presented are the results of this search, and there was no further differentiation about, for example, the maturity of the respective tools. The authors emphasise the following limitations of the search approach. First, as the search was carried out by hand, the overview is not considered to be exhaustive. Second, some tools clearly labelled as designed for biomimetics or in the context of biomimetics – for example, by their title or description – were included in the overview, even though their content was not described in the scientific literature (e.g. Biologically Inspired Problem Solving (BiOPS)[28]). These tools were identified through general Web searches or were known by the authors due to their background and their networks. Third, as some tools which were added to the overview are available only in German, it is to be expected that other tools may exist in a language not manageable by the authors, and therefore, they were overlooked. These are unavoidable limitations of the information that is currently available; however, the authors assume the presented set of tools, designed for biomimetics, to be representative.

2.2 Qualitative analysis: definition of variables and classification of tools

Although existing tools and methods have been described and compared in the literature (e.g. Fu *et al.*,[1] Stone *et al.*,[22] Glier *et al.*,[23] Goel *et al.*,[24] Nagel and Stone[25]), a comparative evaluation of existing biomimetic tools has been described in only two publications. Fu *et al.*[1] described six biologically inspired design methods and tools and differentiated between cognitive and implementation factors. They pointed out whether the respective factors are well addressed by the tools or whether there is an opportunity to address them. Fayemi *et al.*[26,29] evaluated existing tools by using workshops. They used theoretical and practical indicators to evaluate the use of tools.

In order to contribute to a deeper understanding of existing tools, a qualitative analysis has been performed in this work. The authors focused on a descriptive analysis of the identified tools and the classification of implementation factors. This classification establishes the foundation for further theoretical analyses, which will include more variables for a critical and derivative analysis to examine the value of tools and how they can be used for biomimetics in Practice. The variables were chosen in line with the work of Fu *et al.*[1] and Fayemi *et al.*,[26,29] but were extended with further descriptive variables. Fu *et al.*[1] categorised their evaluation descriptively (from ‘well addressed’ to ‘opportunity to address’); in the study presented here, the variables were extended with nominal or ordinal categories (Table 1; see also Section 2.3).

The classification of each tool was done based on the literature or other available resources – for example, websites or handbooks. Therefore, it describes an extract from published data. The classification was done by the first author, and it was verified by the second author. Both researchers agreed on the classification. A subset of tools (n = 6) was classified only by the first author as these tools were not commonly accessible owing to

Table 1. Variables used for the qualitative classification of tools together with their respective categories

Variable	Category option
v1: class	Abstraction, application, analysis, transfer
v2: type	DSC, taxonomy, thesaurus, ontology, algorithm, method
v3: step of the process	Step 1 to step 8
v4: approach	Solution-based, problem-driven, both
v5: accessibility	Open-source, limited, commercial
v6: availability	Online, software, print
v7: field of knowledge	Biology, technology, both
v8: dimension	Stand-alone, needs previous step, facilitates following step, needs previous step and facilitates following step
v9: sustainability	Yes, no
v10: proof of concept	Yes, no

DSC, database/static list/catalogue

language-related issues. The BioM Innovation database[3] was used to gather data on the usage of different tools in practice.

The limitations of this classification are, first, some tools were classified only by the first author. It was decided to include these tools so that the overview is as extensive as possible. The verified classification of 37 tools led to a clear understanding and description of the variables and their categories. Therefore, it is to be expected that the classifications of the six singly classified tools are comparable to the rest. More critical variables in terms of subjective interpretation were excluded and will be used in further studies which shall involve feedback from the developers of tools themselves. Furthermore, the development of a model of classifying and analysing tools semi-quantitatively is in progress. Most of the tools require deeper understanding and/or training. In order to describe the value of these tools, their use could be examined in workshops, as, for example, described by Glier *et al.*,[30] which is an ongoing research. The presented results build the foundation for these analyses.

2.3 Description of variables

Ten variables were defined for a qualitative classification. They serve to describe the characteristics of the tools, what type of tool they are, which step of the process they facilitate, how they are accessed, whether they contribute to the field of knowledge in biology or technology, whether they can be used as stand-alone or depend on other steps, whether they were used in case studies and whether they are developed to address sustainability issues.

2.3.1 v1: class

Referring to Fayemi *et al.*,[26,29] tools were classified accordingly to the definition of biomimetics[10] into the classes of analysis tools, abstraction tools, application tools and transfer tools. This classification is in line with the process description, defining eight steps

- step 1: problem analysis (analysis)
- step 2: abstraction of the technical problem (abstraction)
- step 3: transposition to biology (transfer)
- step 4: identification of potential biological models (application)
- step 5: selection of biological model(s) of interest (analysis)
- step 6: abstraction of biological strategies (abstraction)
- step 7: transposition to technology (transfer)
- step 8: implementation and test of the concept in the initial context (application).

2.3.2 v2: type

According to the earlier mentioned definition of a tool, existing tools were classified as *something* used in performing or supporting the process of biomimetics. This something was differentiated as database/static list/catalogue (DSC), taxonomy, thesaurus, ontology, algorithm or method. These terms are defined as follows.

A DSC is a collection of biological organisms, biological characteristics, biological construction principles, biological functions or the like. This list changes or evolves only if updated.

A taxonomy is an orderly scientific classification categorising certain principles.

Thesauri aim at facilitating communication. They function as a type of dictionary, translating biological terms into their technological equivalents and/or vice versa.

Ontologies in the present context aim to categorise biological principles and abstract the diverse phenomena of biology into descriptive functions. Tools classified as ontologies in this paper encompass those which are already implemented as an ontology.

An algorithm is an automated procedure for solving a certain task in a finite number of steps. In the context of this study, tools were classified as algorithms if they describe a set of steps which help to complete a task of the biomimetic process. It is not necessary that these tools are implemented as software.

A method describes a way of doing a task during the process of biomimetics.

2.3.3 v3: facilitated step of the process

The problem-driven process of biomimetics is described with eight steps (see Section 2.3.1).

The steps of the process refer to the classes mentioned under v1: analysis tools (step 1 or step 5), abstraction tools (step 2 or step 6), application tools (step 4 or step 8) and transfer tools (step 3 or step 7).

The overview of the steps given for v1 shows that each class covers two steps of the process; therefore, v1, class, and v3, facilitated step of the process, are closely connected. As tools may exist which belong to a certain class but facilitating only one of the steps of the process, these two variables were distinguished. For instance, there may be application tools which facilitate the identification of potential biological models (step 4), but they do not facilitate the implementation in technology (step 8).

The distinction between v1 and v3 allows the identification of the number of tools facilitating certain steps of the process. This analysis will enable the identification of lower or higher representations of tools for certain steps and may indicate further developments of tools.

If tools facilitate more than one step, they were accounted for each step – for example, structure–function patterns[23] may serve as keywords for the search of biological models (step 4) and they can assist designers to abstract biological systems (step 6).

2.3.4 v4: approach
In most cases, it was not specifically indicated by the developers whether the tools were developed for the solution-based[7] or problem-driven[5,31] approach of biomimetics. The tools were therefore classified according to their potential usage for one or both of the approaches. As several steps of both approaches and their underlying tasks are similar – for example, the communication across interdisciplinary boundaries – tools facilitating these steps were classified as being for both approaches. A tool which is classified as for the solution-based approach only can be used, for example, for the idea generation of biologically inspired designs rather than for facilitation of a concrete transfer of biological strategies to generate a solution for a concrete problem, as would be necessary for the problem-driven approach. If a tool is classified as being for the problem-driven approach only, it focuses on finding biological models for a defined problem and therefore does not facilitate the solution-based approach.

2.3.5 v5: accessibility
To describe whether a tool is accessible, the tools were classified as (*a*) freely available literature and/or computational tool (open-source), (*b*) available but with limitations – for example, as a demo version only (limited) or (*c*) commercial if they can be purchased.

2.3.6 v6: availability
In contrast to accessibility, tools were furthermore classified according to their origin, as an online hosted, a printed or a software version.

This variable serves to give insight about the overall availability of the tools. Therefore, when a tool was described in the literature and was also online hosted, it was classified for the online hosted version as this emphasises its availability.

2.3.7 v7: field of knowledge
It was distinguished whether the tools and/or their usage addresses the body of knowledge in either biology, technology or both fields. If a tool is related, for example, to the field of knowledge of biology, it contributes by, for example, structuring, relating or clustering biological knowledge and therefore contributes to deeper insights in biology.

2.3.8 v8: dimension
For the description of the dimension of a tool, it was classified whether the tool can be used as a stand-alone tool, whether it needs a previous step or whether it facilitates the following step, in order to point out the interconnectedness of tools.

2.3.9 v9: sustainability
This variable was introduced in order to clarify whether a tool was specifically developed to increase the impact of biomimetics on sustainable and responsible innovation.

2.3.10 v10: proof of concept
If a tool was used for the development process of a product, as far as known from the BioM innovation database,[3] it was classified positively with a proof of concept. Tools which were evaluated in case studies (theoretical or practical ones) in literature have also been classified as yes. Otherwise, they did not have a reported proof of concept so far.

3. Results and discussion

3.1 Overview of existing tools
Table 2 shows the overview of the 43 identified tools and methods which were developed to facilitate the process of biomimetics. They are presented with the year of publication or their documented development, a brief description and references to the source of publication. The overview is in chronological order of their development.

The search for tools identified some procedures – for example, BioGen[7] or the concept–knowledge design theory[79] – considered to be able to facilitate the process of biomimetics. These were not included as they do not particularly fulfil the definition of a biomimetic tool.

As mentioned before, the presented tools are derived from various disciplines. Therefore, the presentation of these existing tools is the first collection and overview at hand, which enables the reader to get to know this diversity of tools and to use them potentially in the future. The brief description of the tools is considered to help the reader understand the overall aim or context of the respective tool, so that the reader may decide whether to learn more about the tools with help of the references. Together with the results of the qualitative analysis of existing tools, a structured presentation, the interconnectedness of the tools and the mapping of tools to the process of biomimetics are given. These first steps of the analysis of tools are a state-of-the-art description of tools facilitating the process, and they outline the complexity and broadness of the problem-driven process of biomimetics. Furthermore, they build the foundation for future research, which will focus on the usability of tools in Practice, as elaborated in Section 3.3.

Table 2. Full overview of identified tools which facilitate the process of biomimetics (continued on next page)

	Name	Year	Description	References
1	The seven steps of Bionik (Die sieben Denkschritte der Bionik)[32]	1987	Methodology, comparison of biological and technological function, constraints and performance criteria to compare solutions and to measure applicability	Zerbst[32]
2	16 patterns of nature[33]	1995	Classification of biological systems, general overview	Hoagland and Dodson[33]
3	Catalogue of biological principles (Katalog biologischer Konstruktionen)[34]	1998	Static list, biological principles for giving insight on biological construction	Hill[34]
4	Bioanalogous similarity matrix (Bioanaloge Ähnlichkeitsmatrix)[35]	2002	Methodology, comparison of biological and technological system to measure applicability	Küppers and Tributsch[35]
5	The ten fundamental principles of biological systems (Die zehn Grundprinzipien biologischer Systeme)[36]	2002	Static list of ten characteristics of biological systems for a deeper understanding of biology; enables to compare biology and technology and to transpose principles to technology	Nachtigall[36]
6	BidLab search tool – natural language analysis for biomimetic design[37]	2004	Computational tool based on WordNet for searching texts from the biology literature to identify biological analogies	Chiu and Shu[37]
7	Idea-Inspire[38,39]	2005	Software for browsing a database of biological and artificial systems for inspiration and problem-solving	Chakrabarti *et al.*[38,39]
8	A systematic catalogue for biomimetic design (Systematischer Katalog für bionisches Gestalten)[40]	2005	Catalogue of biological systems for a deeper understanding of biological systems and the transfer to technology	Nachtigall and Wisser[40]
9	Bioniquity (Biology – Technology – Creativity)[41]	2005	42 abstracted principles of biological models which can be used for idea generation on the meta level	BMVIT[41]
10	Transfer checklist of biological association (Assoziationsliste)[42,43]	2006	Functional principles of technology which are mapped to selected examples from biology; serves for association	Gramann,[42] Lindemann and Gramann[43]
11	BioTriz[4]	2006	Matrix for the resolution of conflicts derived from biological solutions, refers to the 40 inventive principles of the theory of inventive problem-solving (TRIZ)	Vincent *et al.*[4]
12	Functional modelling[44]	2008	Method for modelling biological systems functionally, aims towards a function-based biomimetic design repository	Nagel *et al.*[44]
13	Systematic reverse engineering of biological systems[45]	2007	Systematic method for reverse engineering of biological systems, assists designers in identifying biological models	Wilson and Rosen[45]
14	Natural language analysis[46,47]	2007	Method for generation and ranking of biologically meaningful keywords to bridge biology and engineering	Chiu and Shu[46,47]
15	Biologically meaningful keywords[48,49]	2008	Defining biologically meaningful keywords referring to the terms of the functional basis	Cheong *et al.*[48,49]
16	Ontology for bioinspired design[50]	2008	Ontology for capturing, retrieving and reusing bioinspired design solutions based on associated physical architectures, behaviours, functions and strategies; aims towards internal repository	Yim *et al.*[50]
17	AskNature[19,20]	2008	Publicly available database of biological information classified by functions	Deldin and Schuknecht[19]
18	Biomimicry Taxonomy[19,51]	2008	Static list organising biology by function and abstracted functional principles	Deldin and Schuknecht[19]
19	SAPPhIRE (State change–Action–Part–Phenomenon–Input–oRgan–Effect) model[39,52]	2005	Model used to represent biological or artificial systems	Chakrabarti *et al.*,[39] Chakrabarti[52]
20	Categorisation of natural language keywords[53]	2010	Method for categorisation of keywords to improve effectivity of identifying biological phenomena	Ke *et al.*[53]
21	Functional modelling – category and scale[54]	2010	Method for modelling biology	Nagel *et al.*[54]
22	Engineering-to-biology thesaurus[55]	2010	Thesaurus correlating biological terms to engineering based on the functional basis lexicon	Nagel *et al.*[55]
23	Nature-inspired design principles[56]	2010	Natural principles based on Biomimicry 3.8's life's principles and cradle-to-cradle principles	Delft University of Technology[56]
24	BiOPS[28]	2010	Thesaurus and dictionary for bridging technology to biology, for identification of biological models; link to patent database	Fraunhofer IAO[28]
25	DANE (Design by Analogy to Nature Engine)[57,58]	2010	Computational tool, database of biological Structure-Behavior-Function (SBF) models	Vattam *et al.*,[57] Design Intelligence Lab[58]
26	Automatically populating the Biomimicry Taxonomy for scalable systematic biologically inspired design[59]	2012	Method for supporting structuring and selection of biological designs and classifying biological analogies into the Biomimicry Taxonomy	Vandevenne *et al.*[59]

Table 2. Continued

	Name	Year	Description	References
27	Automatic extraction of causally related functions from natural-language text for biomimetic design[60]	2012	Tool for identifying relevant linguistic patterns in biological text	Cheong and Shu[60]
28	A computational approach to biologically inspired design[8,61]	2012	Algorithm for biologically inspired concept generation	Nagel and Stone,[8] Design Engineering Lab[62]
29	Life's principles[11,63]	2008	26 fundamental principles of biology, refers to sustainability	Baumeister *et al.*,[11] Benyus[63]
30	Biologue[64,65]	2013	Interactive online information system for collaborative semantic annotation of biology articles, leading to internal repository; search engine for semantically annotated biology articles	Vattam and Goel,[64] Design & Intelligence Laboratory[65]
31	Ontology of biomimetics[66]	2014	Ontology of biological functions, refers to the 40 innovative principles of TRIZ	Vincent[66]
32	bionicinspiration.org[67]	2014	Website offering bionic categories and case studies	bionicinspiration.org[67]
33	Ontology Explorer[68,69]	2014	Web tool for identification of biological models and exploring biomimetics database	Kozaki *et al.*,[68] Kozaki[69]
34	Unified ontology for causal-function modeling in biologically inspired design (UNO-BID)[70]	2014	Process description, including biomimetic tools	Rosa *et al.*[70]
35	Four-Box method[9]	2014	Problem formulation and analogy evaluation; describes function, operational environment, specifications and performance criteria of systems	Helms and Goel[9]
36	T-chart[9]	2014	Analogy evaluation, comparison of biological and technological systems	Helms and Goel[9]
37	Bioscrabble[71]	2014	Software supporting search term-based extraction of biological analogies out of large text sources, supports managing results	Kaiser *et al.*[71]
38	BioP-C: the Biology Phenomenon Categorizer[72]	2014	Computation game; collects computable knowledge about biological phenomena and assesses their quality; benchmarks are AskNature, Dane, Idea-Inspire and natural-language search tools	Arlitt *et al.*[72]
39	Biotransferability framework[73]	2014	Combination of stochastic multicriteria acceptability analysis with criteria from biologically-inspired design (BID) to evaluate the utility of biological analogies and the biology-to-engineering risk	Williams *et al.*[73]
40	Structure–Function Patterns[74]	2014	Table of biological structure–function patterns, provides keywords for searching biological databases, helps to abstract biological texts, for identifying biological models, useful for idea generation	Helfman Cohen *et al.*[74]
41	Design Study Library[75]	2015	Web tool, searches case studies of a digital library, supports analogical learning	Goel *et al.*[75]
42	Nature-inspired solutions[76,77]	2015	Design principles and methodology, biological principles for sustainable innovation	Karim Network[76]
43	Resilient Design cards[78]	2015	Based on design principles found in nature, methodology for sustainable innovation	ResilieNtWeb[78]

3.2 Qualitative analysis

The full classification of six tools as an example for each type of tool is shown in Table 3. The charts and graphs in this section summarise the classification of the existing tools. In addition, cross-connections between variables are presented.

3.2.1 Development of tools: 1987–2015 (n = 43)

Figure 2 shows that over the past decades, tools have been consistently developed, with an increase in the number of tools in 2014. The graph does not give insight into whether the developed tools were an update or improvement of an existing tool or a new development.

It is assumed that recent tools consist of newer knowledge on biomimetics. However, as scientific literature on biomimetics reached a peak with nearly 3000 publications per year in 2013,[2] it remains an open question whether this knowledge has influenced the development of tools facilitating the process of biomimetics. There do exist methods of a structured way of extracting principles from, for example, the body of biological literature for several purposes,[74,80] and these approaches could be adapted for this endeavour.

In order to identify more tools in the future, it would be helpful to have commonly used keywords and a clear naming of tools.

3.2.2 Classes of tools (n = 43)

If tools facilitate various steps of the process, they were counted for each class respectively. Most of the analysed tools serve as transfer (33%) and application (37%) tools, while in comparison, analysis (12%) and abstraction (18%) tools are less represented.

Table 3. The full classification of tools developed to facilitate the process of biomimetics

Variable	Category option					
	AskNature[19,20]	Biomimicry Taxonomy[51]	Biops[28]	Ontology Explorer[68,69]	Automatically populating the Biomimicry Taxonomy for scalable systematic biologically inspired design[59]	Functional modelling[44]
v1: class	Application	Transfer	Transfer, application	Application	Application	Abstraction
v2: type	DSC	Taxonomy	Thesaurus	Ontology	Algorithm	Method
v3: step of the process	Step 4	Step 3	Step 3 and step 4	Step 4	Step 4	Step 6
v4: approach	Both	Problem-driven	Problem-driven	Problem-driven	Both	Both
v5: accessibility	Open-source	Open-source	Limited	Open-source	Limited	Open-source
v6: availability	Online	Print	Online	Online	Print	Print
v7: field of knowledge	Both	Technology	Both	Technology	Both	Biology
v8: dimension	Needs previous step and facilitates following step	Needs previous step and facilitates following step	Needs previous step and facilitates following step	Stand-alone	Needs previous step and facilitates following step	Needs previous step and facilitates following step
v9: sustainability	Yes	No	No	No	No	No
v10: proof of concept	Yes	Yes	Yes	Yes	Yes	Yes

The table shows the respective classification for one tool of each type

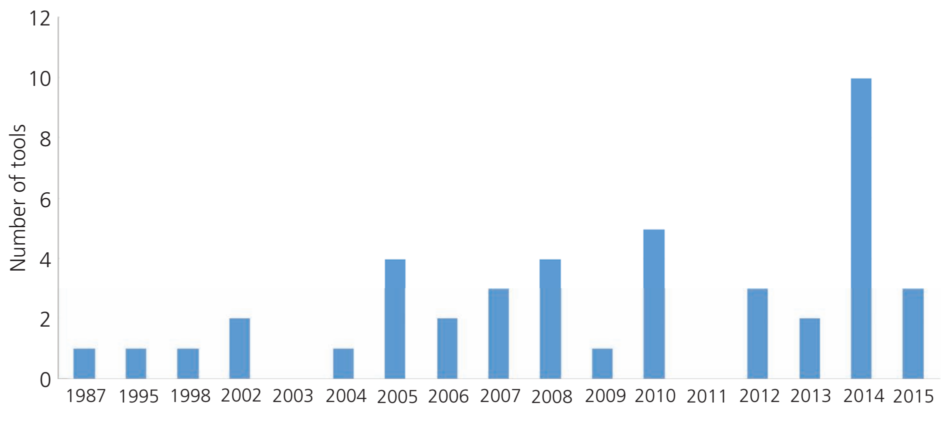

Figure 2. Number of tools published per year (1987–2015)

All four classes cover two steps of the process and focus on tasks in the field of technology or biology. In future research, the following shall be analysed: how existing tools are used at present, where challenges remain, which users' needs exist and whether the usage of tools fosters the success of the respective steps.

3.2.3 Type of tools (n = 43)

Thirty-seven per cent of the analysed tools are DSC. According to their basic definition, they change only if updated and offer a prescribed amount of knowledge. Considering the increase of scientific literature,[2] existing databases or catalogues have the potential to evolve and grow over time. However, this is a very time-consuming task, so other tools apart from databases were developed to screen scientific literature and update automatically (e.g. Kaiser *et al.*,[71] Vandevenne *et al.*[81]).

Only one taxonomy was identified, which is the Biomimicry Taxonomy.[19,51] This taxonomy categorises biology in terms of function and helps to address biology.

Two thesauri were identified.[28,55] As the communication across interdisciplinary boundaries is one of the described challenges,[6] these tools were designed to overcome this challenge and to bridge the gap between disciplines (see Figure 1).

In this study, three ontologies were identified. The ontologies focus on describing nature with abstracted functional principles[51,66] and serve different objectives; one of these is the Ontology Explorer.[68,69]

Algorithms (30%) and methods (19%) both address a systematic way of performing a certain step of the process.

Some tools and methods are developed with cross-links to other tools (e.g. Vandevenne *et al*.,[59] Kozaki and Mizoguchi[68]). This aspect points out the potential for co-creating tools. Further research is needed to elaborate on this idea.

3.2.4 Application to biomimetic approaches (n = 43)

All classified tools facilitate the tasks of the problem-driven approach, and in addition, more than half of them can be used for the problem-driven approach only. The other half can be used for overlapping tasks of both approaches. This indicates that there are several tasks in both approaches which are similar and can be facilitated by existing tools. Interestingly, 33% of the BioM case studies were based on the problem-driven approach, which the authors consider to be of more relevance to industry needs. The communication of existing tools might foster their usage in Practice.

No tools were identified which facilitate the solution-based approach only. Such tools could focus on the systematic knowledge transfer from biology to technology, and they could help to access and structure scientific biological knowledge about certain models. Furthermore, such a strategic approach could strengthen the role of biologists and their expertise in biomimetics, which is crucial for the process.[82] As shown with the BioM database,[3] 55% (41 out of 75) of the analysed case studies were derived from the solution-based approach, which means mostly serendipity. Tools focusing on the solution-based approach could shift serendipity to a more deliberate way of accessing biology.

Existing ontologies or catalogues of biological principles already contribute to this aspect; further development could focus on presenting clusters of multifold developments of nature, combined with underlying deep patterns, or presenting individual biological role models with their specific characteristics and phenomena – from the perspective of a solution-based approach. This has already been proposed,[83] and several works have focused on various aspects (e.g. Helfman *et al.*,[74] Cheong *et al.*,[84] Hoeller *et al.*,[85] Yen and Weissburg[86]). As mentioned before, a co-creation could contribute to this task – for example, the functional modelling of biological systems could be included.

3.2.5 Facilitating steps of the problem-driven approach of biomimetics (n = 43)

Figure 3 shows the mapping of existing tools to the steps of the problem-driven approach of biomimetics and is closely connected to the classes of tools. Tools which facilitate several steps were counted for each of the steps.

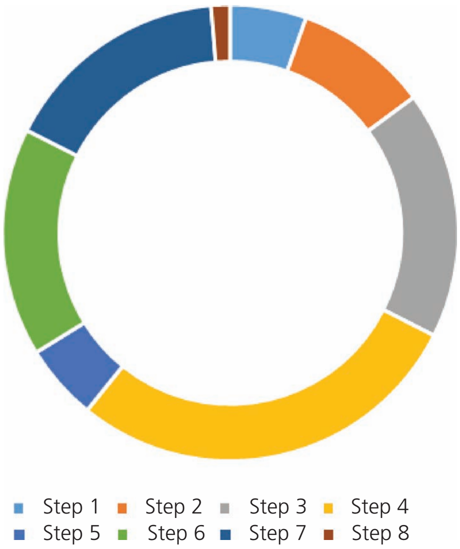

Figure 3. Steps of the problem-driven approach of biomimetics facilitated by classified tools

3.2.5.1 ANALYSIS STEPS

Step 1 of the problem-driven approach of biomimetics is facilitated by four tools. This step serves in analysing the problem. One of the main challenges in biomimetics is defining the problem well enough (e.g. Yen *et al.*[6]) before engaging in the process of biomimetics. One could assume that the usage of tools developed particularly for this step could help to overcome this challenge. It is not necessary that such tools be derived from the community of biomimetics; they could come from other disciplines – for example, the TRIZ community. Step 5, which serves the analysis of biological models and their selection, is facilitated by four tools. Step 5 is a crucial step and further development could help to increase the implementation of biomimetics by bridging the second gap of the process (see Figure 1).

3.2.5.2 ABSTRACTION STEPS

Step 2 and step 6 serve the abstraction of the technical problem or the biological strategy, respectively. Both steps are facilitated by a small subset of tools (step 2: n = 7; step 6: n = 12). It remains an open research question whether these two steps may be facilitated by tools or whether they are mostly dependent on the expertise from individuals of both fields. The authors consider the abstraction a learning process and a new way of thinking about, for example, biological systems, as the abstraction reduces principles of living systems, for example, to their underlying physical-chemical properties in order to make these principles applicable in non-living technical systems. Abstracting biological principles is one of the two most challenging tasks during biomimetics, next to the identification of biological systems.[74] Tools facilitating this step in particular can help to overcome this challenge.

3.2.5.3 TRANSFER STEPS

Twenty-five tools exist which facilitate step 3 and step 7, the transposition from technology to biology and vice versa. These steps are important for bridging both fields of knowledge. Further practical analysis of these tools could measure their impact and their usage.

3.2.5.4 APPLICATION STEPS

Step 4, identification of biological systems, is facilitated by the highest number of tools (*n* = 21). The identification of biological systems seems to have been one of the most prominent steps to work on, as it is the second of the two most challenging tasks.[74] Therefore, many tools have been developed to facilitate this step. As most of the biological species on this planet are still to be discovered and described, the identification of biological models out of the scientific literature remains an ongoing process. This fact also strengthens the necessary role of biologists in the field of biomimetics.[82]

Step 8, implementation and test in the initial context, is facilitated by only one tool and is closely connected to the problem space and the technological application. Therefore, tools from other disciplines may be included to facilitate the steps, not necessarily deriving from biomimetics in particular.

Figure 4 presents the number of tools, distinguished by their type, which facilitate the different steps of the process. It is shown that DSCs and algorithms cover steps 2–7 of the process, while DSCs can also be used for the analysis (step 1) and implementation step (step 8). So far, methods are mainly used not only for the abstraction steps of the process, but also for the selection of a biological model (step 5).

3.2.6 Field of knowledge (*n* = 43)

The knowledge in both biology and technology usually increase during the process of biomimetics as they are connected in a heuristic spiral.[87] At present, around one fifth of the tools contribute to the knowledge about biological systems, while 37% of the tools contribute in particular to the area of technology. 42% contribute to both fields. Further research on the underlying principles of knowledge transfer in biomimetics could contribute to a better understanding of needs and how to overcome them. This aspect could lead to a deeper understanding of the process in Practice and may lead to an improvement of the state of the art.

3.2.7 Availability and accessibility (*n* = 43)

Most of the tools (65%) are described only in the scientific literature, and the information about their objectives and potential is available through literature. It remains an open research question whether this fact limits the usage of existing tools, particularly in the field of industrial application. A further theoretic analysis of the existing tools, based on the data presented in this paper, could therefore help to bridge communication gaps and to open the access to the high potential of the existence of tools. Combined with practical analyses of tools, a contribution to the future evolution of biomimetics towards a broader concept could be achieved.

More than 48% of the tools are available as open-source, while 46% offer limited access. The developers of the AskNature database[20] stated that the provision of a free and publicly available tool is important.[19]

If the tools in the future are more often available freely, the necessary interdisciplinarity of the biomimetic process could be enhanced as beneficiaries from various disciplines have access to tools and may share resources. Such a trend could lead to the improvement of the process, as it would open the process towards the involvement of more people with diverse expertise.

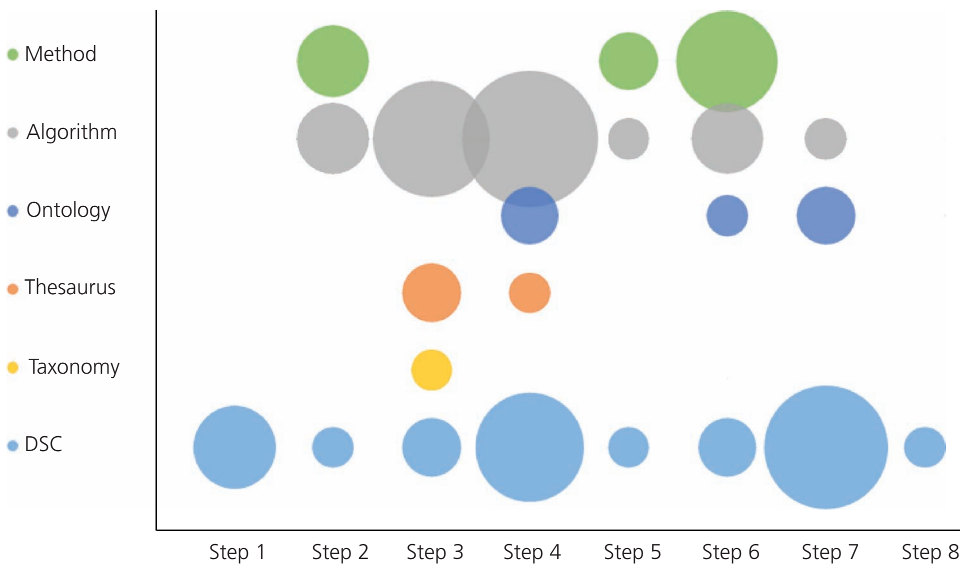

Figure 4. Type of tools facilitating the eight steps of the problem-driven approach of biomimetics. The size of the bubbles indicates the number of tools

3.2.8 Proof of concept (*n* = 43)

Seventy-seven per cent of the classified tools were tested in theoretical or practical case studies, as described in the respective literature. Theoretically, the tested tools have shown their potential for usage in the process of biomimetics, but as mentioned before, they do not seem to be used widely.[3] Only the AskNature website[20] was mentioned in interviews with the developers and then mostly as a means of motivation to explore their own process.[3] Further research on the impact, successes and challenges of single tools in Practice could contribute to the improvement of the state of the art. This research could be done by workshops or interviews with industrial partners.

3.2.9 Dimension (*n* = 43)

It has been reported that the process of biomimetics is not linear, but rather consists of feedback loops and iterations (e.g. Badarnah and Kadri,[7] ISO,[10] Baumeister *et al.*[11]). This statement is strengthened by the classification, as 60% of the tools facilitate next steps, need previous steps or do both. Forty per cent of the tools can be considered to be stand-alone. It could be tested whether the stand-alone capacity could foster the usage and the impact of respective tools. Future analyses shall be used to clarify the impact of the interconnectedness of tools on the process. It could also be analysed whether the classified tools were developed individually, so that the state of the art could be improved if interconnected steps and their tools are taken into account during the improvement of existing or the development of new tools.

Further studies will focus on the connectedness of tools and their potential interdependencies. Practical analyses, such as workshops, shall follow, be it on teaching students or for training of beneficiaries from the business sector. Further research needs to be done in order to identify different needs and gaps, in order to check the appropriateness of tools for different audiences (e.g. Fu *et al.*[1]).

3.2.10 Sustainability (*n* = 43)

Five of the 43 analysed tools were developed with the objective of addressing the environmental sustainability of biomimetic concepts in particular. The contribution of biomimetics to more sustainable innovation is discussed in various aspects (e.g. ISO,[10] Reap and Bras,[80] De Pauw *et al.*,[88] Reap *et al.*,[89] Mead[90]), and in this classification, no detailed analysis was performed. It was only distinguished whether the tool itself contains aspects which address particularly the environmental sustainability of the target concept. Still, research on how to assess the impact of biomimetic concepts on environmental sustainability is ongoing (e.g. Antony *et al.*[91]). Once more tools are identified which address sustainability in particular, further research could evaluate how to include the potential of biomimetics for sustainability in the whole process and at certain steps.

3.3 Use of tools in Practice and outlook

As shown in Figure 5, tools can be used for the process of biomimetics. Most of the tools were developed individually and independently, whereas with the presented work, the authors aimed to point out that these tools can be used together in practice (see also Fayemi *et al.*[26]). Variable v10, proof of concept, shows that more than three out of four of the presented tools have been analysed in theoretical or practical case studies to show their value. If one wants to implement biomimetics in Practice and is facing several challenges (as shown in Figure 1), the respective tools can help to overcome those challenges. Figure 5 shows an example of how to make use of the presented tools in practice by using them at certain steps of the process.

This general example gives a generic overview about how tools can be mapped to the process; it does not specify or analyse the problem which shall be solved through a bioinspired solution. Further analysis of the tools can help to assess the value of tools in Practice, which can be done, for example, through training of users and assessing their success with certain tools. The results of this research have led to a framework of the usage of tools.[92] Furthermore, ongoing research will help to assess the value of tools for certain problems, contexts and desired aims of the process – for instance, the aim for a functional optimisation of products or for a more sustainable product development. The following research questions will be addressed in the future.

- How can the suitability for biomimetics for certain problems be assessed?
- Which tools can be used to perform the defined tasks of the process of biomimetics?
- How are the tools interconnected?
- How can users be helped to choose an appropriate tool?

4. Conclusion

The presented study has given an overview of existing tools which facilitate the process of biomimetics and its problem-driven approach

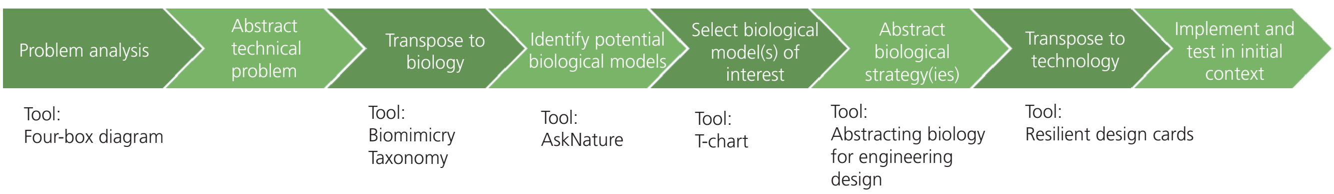

Figure 5. Potential use of tools in practice. Tools can be chosen for certain steps of the process of biomimetics (see Fayemi *et al.*[26,29]) to facilitate the underlying tasks

in particular. This overview has been lacking so far; this study is the first presentation of 43 tools with their connections to the process, and it presents the diversity of biomimetics in terms of research communities and their respective areas of interest. Not only do results from scientific biomimetics contribute to the process, but so do results from other linked disciplines, such design, engineering, product development, creativity or cognition. This diversity is the product of the complexity of biomimetics, which the authors consider to be challenging, particularly for non-experts, but with significant potential for closer collaboration of research areas and stronger interdisciplinary and, more importantly, transdisciplinary co-operation and communication, as well as a fostered knowledge transfer between the academia and industry. Therefore, the presented overview forms the foundation for a broader usage of the tools as potential users find a summary of the scattered tools. In addition, based on this overview and the first analysis which shows the interconnectedness of tools, further research can be performed – for example, through workshops and interviews which help to identify the value of certain tools. This is ongoing research. Furthermore, it was shown that the analysis of tools may lead to improvements of the state of the art, which can be achieved only collaboratively.

The presented work is in progress and is the foundation for a future theoretical statistical analysis. Such an analysis can also encompass analyses of target audiences and their needs, in order to foster the implementation and usage of biomimetics and its tools in education and application. Further theoretical analysis of existing tools is planned in order to identify the principal characteristics of the tools and the underlying patterns of their objectives, successes and drawbacks. Future work is also considered to take into account feedback from the developers and from beneficiaries. This analysis is supposed to draw conclusions for the current process of biomimetics and for the development of new tools. It will be interesting to see how existing and new tools will address current challenges and how they will be designed in order to support different groups of users.

With an increase of research and development in biomimetics in various disciplines, the authors look forward to the option that the well-known potential of biomimetics to become a paradigm in several technological disciplines[2] might be expanded to other fields of research and application. This could lead to an increase in nature-inspired solutions to address the most challenging problems of the present time.

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TOPICAL REVIEW

Biomimetics: process, tools and practice

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Abstract

Biomimetics applies principles and strategies abstracted from biological systems to engineering and technological design. With a huge potential for innovation, biomimetics could evolve into a key process in businesses. Yet challenges remain within the process of biomimetics, especially from the perspective of potential users. We work to clarify the understanding of the process of biomimetics. Therefore, we briefly summarize the terminology of biomimetics and bioinspiration. The implementation of biomimetics requires a stated process. Therefore, we present a model of the problem-driven process of biomimetics that can be used for problem-solving activity. The process of biomimetics can be facilitated by existing tools and creative methods. We mapped a set of tools to the biomimetic process model and set up assessment sheets to evaluate the theoretical and practical value of these tools. We analyzed the tools in interdisciplinary research workshops and present the characteristics of the tools. We also present the attempt of a utility tree which, once finalized, could be used to guide users through the process by choosing appropriate tools respective to their own expertize. The aim of this paper is to foster the dialogue and facilitate a closer collaboration within the field of biomimetics.

1. Introduction

For over 3000 years, people have 'learned from nature' in order to inspire human design (Vincent *et al* 2006). Several terms exist to describe the concept of 'learning from nature' (see section 2.1) and as a systematic approach it is still an emerging field of research, especially within engineering design (Von Gleich *et al* 2010). Biomimetics encompasses a broad variety of research topics, it impacts several fields of application and it is considered to have a significant scientific, societal and economic impact for the quality of life (Lepora *et al* 2013). However, research areas are broad and fragmented and most of the significant results have remained in their own field. Studies have shown that biomimetics has been practiced primarily by individual parties rather than through an institutionalized approach (Von Gleich *et al* 2010), and that the relatively low number of documented biomimetic products on the market is due to several reasons (Goel *et al* 2013), one of which is the lack, from a general perspective, of a clear methodology in the field (Vincent *et al* 2006). To contribute to the research in the field, we analyzed the process of biomimetics and existing tools which facilitate the process, with the aim of making the existing tools and the information about the process more transparent for potential users. First, we give an overview of terms and definitions to clarify the terminology. Next, we present a unified problem-driven process model of biomimetics as a framework for the practical implementation of biomimetics. Lastly, we assessed tools, which are reported as being used within a bioinspired design process, in order to validate their facilitation of the process and to gain knowledge about users' perception of the tools. The assessment was performed with three small-sized workshops involving highly specialized professional profiles (i.e. bioinspiration and problem-solving experts) as well as through a broader field survey. This analysis resulted in the design of a 'utility tree' which provide a guiding through the process model by using appropriate tools. This presentation is considered to be a first attempt and further studies will serve the purpose of improving this utility tree. We consider experts from various disciplines (e.g. biology, engineering, industrial design, architecture and many more) to be the beneficiaries of our work. The target group is referenced, in this work, as practitioners, i.e. engineering designers.

2. Definitions

Several terms exist to describe the process of 'learning from nature', such as bioinspiration, biomimicry, bionics, or biologically-inspired design (BID). In the scientific literature these different terms are presented as if they were synonyms (e.g. Vincent *et al* 2006, Shu *et al* 2011, Goel *et al* 2013). We consider this appropriate, if one refers to the final outcome of these approaches, which is an invention that has been made possible with knowledge originating from nature. But differences occur by looking at the respective scopes of each word and the development processes (see section 3). For a better understanding of these differences, we provide definitions of important terms.

2.1. Terminology

A recent work within the ISO/TC 266 Biomimetics committee has led to the following definitions (ISO/TC266 2015):

- Bioinspiration: 'Creative approach based on the observation of biological systems'.
- Biomimicry: 'Philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic)'.
- Biomimetics: 'Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution'.
- Bionics: 'Technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents'.

Terms related to bioinspiration can be distinguished according to a specificity of analogy and an axis of related fields, as presented in figure 1. Bioinspiration ranges from mere inspiration fostering creativity in general (related to the divergent phase of creativity), up to novel design solutions (through the implementation of the convergent phase of creativity). This concretization of ideas could either be based on an analogy schema by adapting principles extracted from biology (BID) or through the abstraction, transfer and application of knowledge from a specific biological system (biomimetics).

According to the definitions, field wise (i.e. mechanics, sustainability and other fields), bioinspiration can be specific to mechanics (bionics) (ISO/TC266 2015), specific in its striving for sustainable solutions (biomimicry), or non-specifically labeled, e.g. related to nanotechnology, materials science, architecture, aerodynamics or molecular engineering.

The variety of operational definitions of bioinspiration demonstrates that the field of biomimetics consists of differing subjects and research priorities. Regarding the above outlined definitions, we further refer to the approach of biomimetics.

2.2. The two approaches of biomimetics

In general, biomimetics practice can be carried out either as solution-based (solution-based Helms *et al* 2008, Badarnah and Kadri 2015, solution-driven Vattam *et al* 2007, Helms *et al* 2009, biology to design Baumeister *et al* 2013, biology push ISO/TC266 2015, bottom up Speck *et al* 2008, biomimetics by induction Gebeshuber and Drack 2008) or as problem-driven (problem-based Badarnah and Kadri 2015, problem-driven Vattam *et al* 2007, Helms *et al* 2008, 2009, challenge to biology Baumeister *et al* 2013, technology pull ISO/TC266 2015, top down Speck *et al* 2008, biomimetics by analogy Gebeshuber and Drack 2008). Both the solution-based and problem-driven approaches have different starting points and differing characteristics as design processes (Goel *et al* 2014).

The solution-based approach describes the biomimetic development process in which the knowledge about a biological system of interest is the starting point for the technical design. The biological system of interest performs a function that shall be emulated in technology. This biological system must be understood in depth in order to extract underlying principles and to define design problems which could be addressed using these principles. The knowledge concerning these principles is primarily gained from fundamental research. After their abstraction the biological principles may be applied in technology. The solution-based approach is therefore closely connected to the steps of the technology knowledge transfer process from scientific to industrial organizations. Such process is usually applied by Technology Transfer Office and involves the following steps: Scientific Discovery, Invention Disclosure, Evaluation of invention for patenting, Patent, Marketing of Technology to firms, Negotiation of License, License to firms (Siegel *et al* 2004).

On the other hand, the problem-driven approach is the biomimetic development process that seeks to solve a practical problem, with an identified problem to be the starting point for the process (Goel *et al* 2014, ISO/TC266 2015). New or improved functions may be applied via identifying biological systems, which

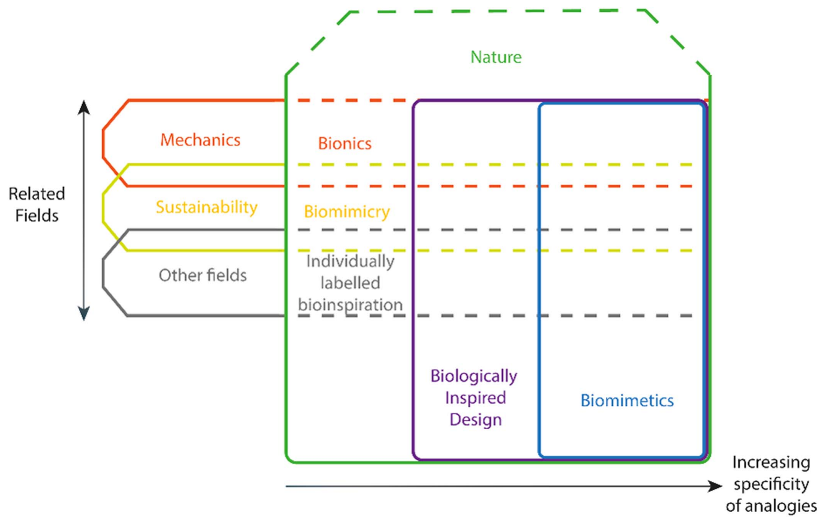

Figure 1. The field of bioinspiration.

perform a certain function or mechanism, and by abstracting and transferring these principles to technology. The problem-driven approach is closely connected to the problem-solving process. Models of this process have already been described within literature (e.g. Bransford and Stein 1984, Isaksen and Treffinger 1985, Adams *et al* 2003, Bardach 2011). The problem-solving process has been summarized by Massey and Wallace's (Massey and Wallace 1996) consisting of 5 stages: identification, definition, alternative generation, choice of solution and implementation and testing.

Both approaches show intrinsic differences and a deeper understanding of each of the processes requires a detailed analysis. The aim of this paper is to foster the usage of biomimetics in the industrial sector. Therefore, the following presented work will focus on the problem-driven approach of biomimetics, as this approach seems more appropriate to be initiated by industrial companies (i.e. the process starts within the technical field)—even though this approach is less represented among commercially available biomimetic products (Jacobs *et al* 2014).

3. Biomimetic process model

Within the last decade the problem-driven approach of biomimetics has often been described in literature (e.g. Vattam *et al* 2007, Helms *et al* 2009, Goel *et al* 2013). A representative set of different presentations of the process is shown in figure 2. Twelve presentations were aligned with the problem-solving process (Massey and Wallace 1996) to illustrate a holistic perspective on the state of the process models.

Lindemann and Gramann (2004) describe a model consisting of four steps strating from the formulation of the intention up until the realization of the technical solution. The progression of the steps is connected to iterative loops and internal check lists.

Bogatyrev and Vincent (2008) describe a process which focuses on extracting essential features from biological models and transferring these features to technology by performing a six steps process.

Lenau (2009) presents biomimetics as a process using natural language analysis, which includes subactivities and often requires refinement.

Helms *et al* (2009) outline a problem-driven biologically-inspired design process model as a non-linear and dynamic progression of six steps, including iterative steps as well as feedback and refinement loops.

Nagel *et al* (2010a) implement a concept generation approach for biologically-inspired solutions which uses six steps. These steps start with the functional model of a desired engineering system to explore biological solutions for inspiration and ends with a conceptual or detailed design. This description is intertwined with the development of a specific tool, developed or utilized by its authors. The same holds true for the presentation of the problem-driven process from Chakrabarti *et al* (2005) and Shu *et al* (2010).

Cheong *et al* (2011) outline a process model based on natural language processing. The model starts with the definition of an original functional keyword to describe a problem and ends with the identification of biologically meaningful keywords.

Baumeister *et al* (2013) use their Design Spiral Methodology to address a practical challenge to biology. In a circular eight-step process this Biomimicry Thinking approach is used for the emulation of biologically-inspired design principles.

Goel *et al* (2014) have set up a generic task model of analogical design and have matched it with the solution-based and problem-driven approaches of biomimetics.

ISO/TC 266 (2015) Biomimetics shows an overall simplified flow chart of a biomimetic process. The

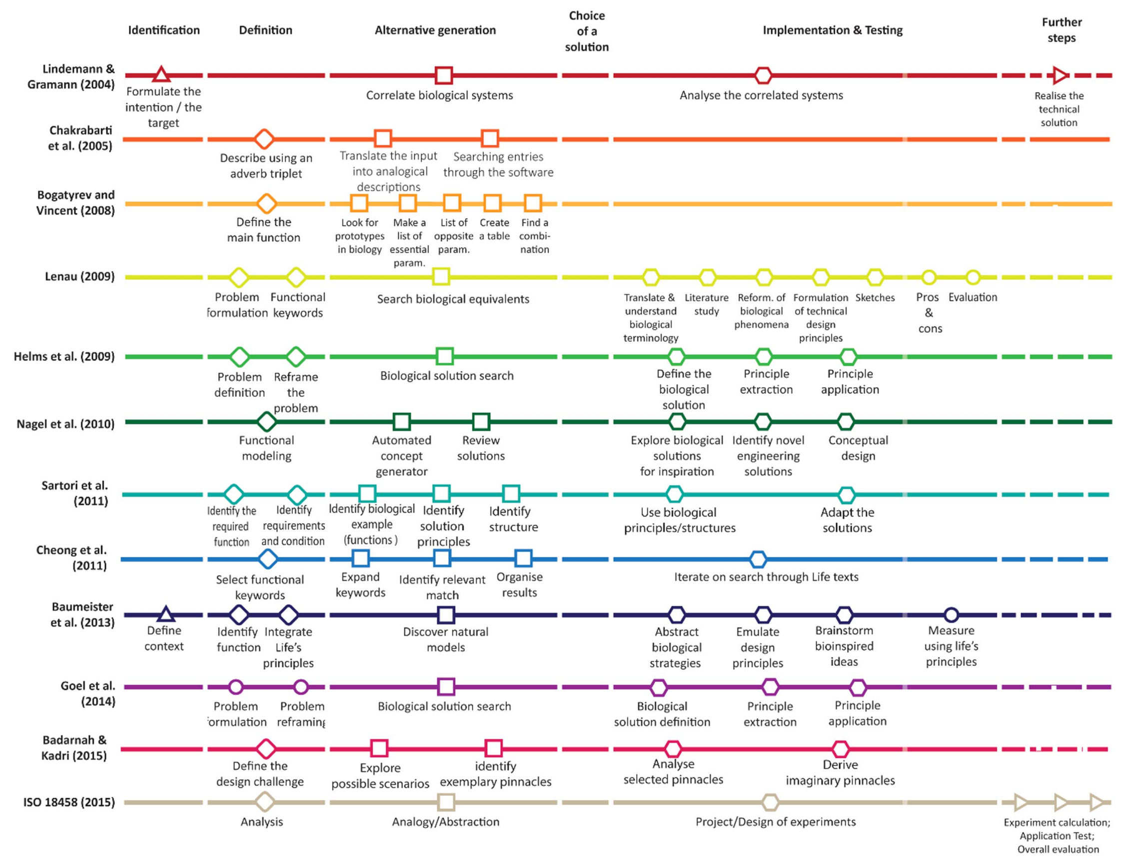

Figure 2. Problem-driven biomimetic process models correlated with the general problem-solving process.

standard points out that the particular sequence of steps during a development process in biomimetics differs within scientific disciplines.

There have already been attempts in analyzing different descriptions of the process of biomimetics and establishing a general methodology for the generation of design concepts (Sartori *et al* 2010, Nagel *et al* 2014, Badarnah and Kadri 2015). Sartori *et al* (2010) offer a model based on Function-Behavior-Structure (FBS) modeling dividing functions and structures in the search for biological analogies. Nagel *et al* (2014) outline a systematic biologically-inspired design methodology which closely follows five steps of the problem-solving model (Massey and Wallace 1996), presenting flowcharts of the problem-driven approach, with cues for iteration. Badarnah and Kadri (2015) present their BioGen methodology that enables designers, especially architects, to face the challenges of the process of biomimetics by following several phases. Furthermore, they present tools that facilitate the implementation of different phases.

4. The unified problem-driven process of biomimetics

Biomimetics demands from potential users a deeper insight into existing process descriptions and the knowledge about existing tools (ISO/TC266 2015). Therefore, we consider it to be beneficial to unify the above mentioned descriptions. The purpose is to give practitioners a better understanding of the field by combining the existing process models.

Figure 3 shows the unified problem-driven process model consisting of eight steps. The outline of the process model is divided in two phases designed as a double symmetrical abstraction-specification cycle. The first phase (step 1–4), focuses on a technology to biology transition while the second phase (step 5–8) tackles its way back from biology to technology. The required contribution of either biologists or technologists are indicated with the light (biology) and dark (technology) arrows.

The initial entry point of the unified biomimetic process model, is the problem analysis (step 1). This can either encompass the assessment of the situation and/or the problem description. In the first case, a specific problem to address has not yet been identified. Step 1 then aims to identify a development axis of improvement for the technical system of interest and focuses on system optimization. In the latter case, a concrete problem has already been identified and the problem description provides a proper problem formalization. The abstraction of the technical problem (step 2) leads to a functional model which encompasses the context as well as constraints of the problem. After this, it is clear which function should be achieved. With this abstraction and the envisaged

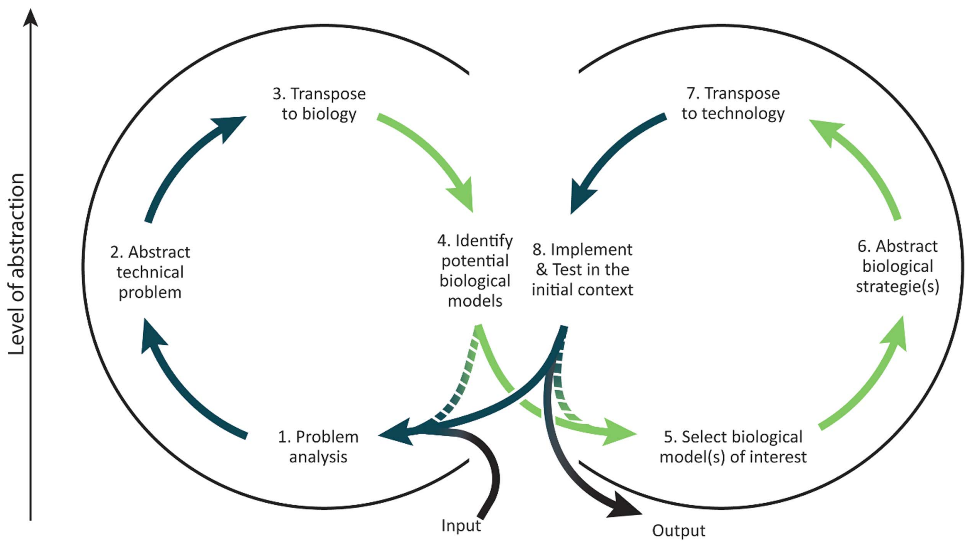

Figure 3. The unified problem-driven process of biomimetics.

function, the problem and its environment can be transposed to biology (step 3). Usually, a question towards nature is formulated in order to explore how nature has achieved a certain function. This is an important step, as the results may highly differ depending on how the question was formulated. With the transposed question, biological models can be identified by searching through literature, using web engines and databases, or by gathering existing knowledge. After step 4, there is a first iteration loop. The identification of biological models can lead to a deeper understanding of the initial problem, which might require a new circle of step 1–3. This interaction is due to the fact that a comparison of biology and technology may lead to a gain of knowledge in both fields.

The process is continued by selecting a biological model of interest (step 5). The strategy of the biological model needs to be understood in detail and then abstracted (step 6). Step 5 and 6 allow the combination of several biological models and thus biological principles in order to solve the initial problem (which has been labeled as compound analogy Vattam *et al* 2008, Goel *et al* 2014). The abstraction of the biological strategy is crucial as an exact biology-technology match is usually not feasible. In general, the abstraction leads to a functional model of the biological system (e.g. Helms *et al* 2009), extracting principles independent of the living system (e.g. Baumeister *et al* 2013) which may be emulated in technology. A transposition of the biological strategy to technology is the next step (step 7), which enables designers to embody the outlined biological principles according to technical functionalities. Such transposition usually requires the available technological knowledge to act as a grid for interpreting the biological solution(s) and enabling its implementation into the technical world. The biological to technology conversion then leads to the final implementation and testing in the initial context (step 8). At this point the cycle can be finished successfully with a biomimetic design as output. If the results are not adequate the cycle can either be started all over again or there may be an iteration within phase two, selecting a new model of interest.

The unified biomimetic process model does not pursue the objective of being a new process model per-se but can be rather be seen as an instrument to make existing biomimetic process models converge. With an explicit link to the outlined problem-solving process, practitioners may implement the bio-inspired process more easily, as it is connected to their prior knowledge of such design processes. The unified process is descriptive and leaves space for feedback loops and iterations.

5. Biomimetic tools

Along with the growing interest for bioinspiration (Goel *et al* 2013), tools were designed to fit its specificities (e.g. interaction between technologists and biologists Nagel *et al* 2011, use of biology as a specific source of knowledge Baumeister *et al* 2013). Other tools originating from the design field have also been used for biomimetics (e.g. TRIZ Vincent and Mann 2002, FBS Chakrabarti *et al* 2005, Vattam *et al* 2011a). A combination of tools from these two originating sources defines the biomimetic toolset considered in this work.

Within this work, a set of tools was chosen for analysis, according to the following parameters:

– Biomimetic implementation: has the tool/method been documented as being used in a biomimetic case study?

Table 1. The biomimetic toolset and its match with the steps of the unified problem-driven process of biomimetics.

	Considered tools
Step 1	*S*-Curve, Domino, LP, KLP
Step 2	MSD, Uno-BID, TC, IFR, CW, DANE, SAPPhIRE, 4-Box, 5-Whys
Step 3	IP, Resources, Taxonomy, BIOPS
Step 4	BIOPS, Bioniquity, AskNature, Brainstorming
Step 5	T-chart
Step 6	Uno-BID, DANE, SAPPhIRE, BioM, 4-Box
Step 7	IP, Resources
Step 8	—

– Theoretical description: has the tool/method and its development been described and discussed in literature?

– Illustrative case study: has the tool/method been disclosed in a practical environment?

– Usage guidelines: do the authors provide any document to help the proper use of the tool/method?

These parameters were thought to identify tools which more likely provide a required maturity for an industrial implementation. 22 tools were selected and are shown in table 1.

TRIZ tools were distributed based on Schöfer's work (Schöfer *et al* 2013) which emphasizes Savransky's (2000) and Nakagawa's (Nakagawa *et al* 2003). Other tools were assigned according to a theoretical literature analysis ran by the first author and reviewed by the second. Furthermore, the biomimetic tools were divided into four categories, as shown in table 2, in accordance with creative activities during problem-solving (Wallas 1926, Amabile 1983, Nelson 2003). For consistency, the chosen categories were aligned with the definition of biomimetics (ISO/TC266 2015), which states that the initial problem is solved through the analysis, the abstraction, the transfer and the application of knowledge from biological models to the technical field. Therefore, the four considered categories of tools are: abstraction (preparation Wallas 1926; problem or task identification Amabile 1983; naming Nelson 2003), transfer (incubation Wallas 1926; preparation Amabile 1983; framing Nelson 2003), application (illumination Wallas 1926; response generation Amabile 1983; taking action Nelson 2003) and analysis (verification Wallas 1926; response validation Amabile 1983; reflecting Nelson 2003).

5.1. Analysis tools

The tools identified to facilitate the Analysis step are:

Life's Principles (*LP*). The collection of design patterns from currently living species constitutes the LP (Baumeister *et al* 2013). LP could therefore be used as a measurement instrument and/or as design principles, allowing designers to identify new ways to improve the sustainability of their object of study.

KARIM's version of LP (*KLP*). The European project 'Knowledge Acceleration and Responsible Innovation Meta network' (KARIM) has developed a complement to the KARIM Responsible Innovation manual, based on the LP. This version presents the same principles than the LP (Baumeister *et al* 2013) with sample questions, advantages, and biological and technical examples (Michka Mélo *et al* 2015).

S-Curve. One of the axioms upon which TRIZ has been built is the development of technological systems according to Evolution Laws (Cavallucci and Weill 2001). These laws state that the development of technical products follow certain patterns (Altshuller 1988). From this statement, the *S*-Curve analysis has been developed to identify product life cycle stages and to offer guidelines to move from one stage to another (Terninko *et al* 1998).

Domino. The Domino or Task Analysis, a part of the Synectics which was developed by Nolan (1989), is a four steps questionnaire. The method focuses on reframing a given problem by identifying ownership, foreseeable problems and the problem's root cause (Nolan 1989).

T-Chart. The T-Chart (Helms and Goel 2014) allows the comparison of two 4-Box representations (one for the problem description, one for the identified biological analogues), providing an evaluation of the analogy.

5.2. Abstraction tools

Tools among this category are:

Brainstorming. Brainstorming (Osborn 1953) is a well-known group activity that provides a democratic way to quickly generate many ideas , requires few material resources, and helps foster social interactions.

SAPPhIRE representation. The State change, Action, Part, Phenomenon, Input, oRgan and Effect model (SAPPhIRE) is a causal language developed to describe structural and functional information of both natural and technical systems (Chakrabarti *et al* 2005). Originating from the Function, Behavior, Stucture (FBS) model proposed by Gero (Gero 1990), the model has been made to emphasize the physical phenomena on which the described function relies.

Design analogy to nature engine (*DANE*). DANE is an interactive tool for supporting BID (Vattam *et al* 2011a). It is based on Structure-Behavior-Function (SBF) model (Goel *et al* 2009) which refers to the Functional Representation (Vattam *et al* 2011b). Functions are modeled through a progression of states, linked together by behavioral causal explanations, along with structure box diagrams.

Uno-BID. Uno-BID seeks to combine existing functional-causal models into a single ontology (Rosa *et al* 2014). It thus hybridizes both the detailed description of system internal structure of SAPPhIRE

Table 2. Types of biomimetic tools and their match with the unified problem-driven process of biomimetics.

Step 1: Problem analysis	**Step 2:** Abstract technical problem	**Step 3:** Transpose to biology	**Step 4:** Identify potential biological models	**Step 5:** Select biological model(s) of interest	**Step 6:** Abstract biological strategies	**Step 7:** Transpose to technology	**Step 8:** Implement and test in the initial context
Analysis tools	Abstraction tools	Transfer tools	Application tools	Analysis tools	Abstraction tools	Transfer tools	Application tools

representation (Chakrabarti et al 2005) and the modeling approach provided by DANE (Vattam et al 2011a).

Multi-screen diagram (*MSD*). The MSD (also called System-Thinking Operator, or 9-Windows) is a mental exercise segmenting a technical system into boxes, starting from the central box which refers to the current system, and varying according to two axes, time and systemic levels (Altshuller 1988). By creating a dynamic picture, the multi-screen serves as a reminder to perform a gradual transition between different subsystems and states of technology as any division of a technique into subsystems is arbitrary by nature (Savransky 2000).

Ideal final result (*IFR*). IFR, is about picturing the ideal representation of a system by overcoming current technological limitations. Ideality is reached when an action is fulfilled without the need of the system (Altshuller 1996). The identification of the IFR can be facilitated by methods such as the Innovation Situation Questionnaire, which is a structured thinking questionnaire (Terninko et al 1998).

Technical contradictions. Technical contradictions occur when a system improves a technical characteristic or parameter which at the same time deteriorates another one. Not overcoming technical contradictions leads therefore to trade-off solutions. Technical contradictions are often hidden or vaguely formulated only (Altshuller 1988). As a tool, Technical Contradictions, aim to identify and to define such conflicts.

5-Whys. 5-Whys is an iterative process tool focusing on identifying the root cause of a problem. The technique explores the chain between cause and effect by repeatedly interrogating users on the problem cause (Ōno 1988).

Closed world approach (*CW*). The CW originates from the Unified Structured Inventive Thinking (Sickafus 1997), a derivative of TRIZ (Altshuller 1988, 1996). It provides an analysis of a problem by describing the functional interactions between objects of a given system according to their effect (i.e. useful or harmful) and their attributes (Sickafus 1997).

Four-box method (*4-Box*). The four box method (Helms and Goel 2014) consists of a 2 × 2 matrix, facilitating the problem description according to its Operational Environment, Function, Specifications and Performance Criteria.

Biological modeling (*BioM*). BioM is a set of guidelines proposed by Nagel et al (2011), leading to the functional representation of a given biological system. Generated models may tackle different levels of granularity and the modeling process is facilitated by an engineering-to-biology thesaurus (Nagel et al 2010b).

5.3. Transfer tools

The identified transfer tools are:

Taxonomy. Taxonomy allows designers to translate a technical problem into a biological one thanks to the use of a functional ontology which seeks to organize biology by challenge (Baumeister et al 2013).

Inventive principles (*IP*). Altshuller's work has shown that 40 principles are used by patent authors to solve a problem (Altshuller 1997). Inventive Principles have been outlined to overcome design trade-off. Awareness of these heuristics is important, but knowing which principle(s) to use in order to solve a given problem is equally essential. For this purpose, Altshuller (1997) synthetized the typical design parameters of a system into a matrix of 39 generic parameters. This matrix, known as the Contradiction Matrix, allows designers to link formalized problems through technical contradictions to the inventive principle(s) of interest in order to solve the initial contradiction and thus the problem.

Resources analysis. The problem solving tool Resources Analysis focuses on resources that exist within the analyzed system or its environment. The initial purpose is that providing a database of resources would allow designers to recognize things that they usually might not consider as resources. Once the resources have been identified, the tool uses heuristics that help designers navigate among them (Savransky 2000) with the goal of turning unexpected and harmful things into useful resources.

Biology inspired problem solving (*BIOPS*). BIOPS is developed by Fraunhofer IAO, Germany, and is accessible online as demo version (Fraunhofer). It is a thesaurus for mapping technological functional search terms with biological models. The starting point is a technical problem (e.g. water harvesting) which will then be linked to biological creatures.

5.4. Application tools

Tools among this category are:

AskNature. AskNature, known for being the largest database related to bio-inspiration, is built around the same ontology as Taxonomy. The database seeks to provide knowledge about a biological phenomenon, links to experts and potential design ideas/application (Baumeister et al 2013).

BionIQuity. BionIQuity® is a set of creativity techniques which can be used in new product development and for problem-solving activities (Dell 2006). It provides 42 abstracted principles of biological models, which are referenced in this work as Bioniquity. These principles can be used for idea generation on a meta-level (Dell 2006).

BIOPS. BIOPS has also been considered as an application tool as the tool will, once the transfer step has been completed, further guide the user to the websites asknature.org to find more information, to a patent database (freepatentsonline.com) and to scientific literature (sciencedaily.com).

Table 3. Summary of the assessment criteria.

	Analysis tools	Abstraction tools	Transfer tools	Application tools
Theoretical criteria	Analysis completeness (Ac)	Modeling capacity (Mc)	Transposition precision (Tp)	Uniqueness of solution (Uos)
	Analysis accuracy (Aa)	Systemic levels integration (Sli)	Direction (Di)	Knowledge enlargement (Ke)
	Identification of ideality (Id)	Information filtering (If)	Query Versatility (Qv)	Modularization (M)
	Prioritization (Pri)	Generalization capacity (Gc)	Consistency (Co)	Inventiveness (Inv)
		Constraints preservation (Cp)		
Practical criteria	Swiftness (1) Simplicity (2) Stand-alone capacity (3) Field adaptability (4) Group adaptability (5) Precedence (6)			

6. Experimental method and results

We considered a study on how these tools were perceived by their users as a beneficial step. This study should provide insight into practical context specificities of the tools, while validating the distribution made according to the problem-driven biomimetic process model.

6.1. Assessing the biomimetic toolset

Comparison of creative or problem-solving methods and tools have been attempted several times (Alford *et al* 1998, Cavallucci and Lutz 2000, Shah *et al* 2000, Chakrabarti 2003, Thiebaud 2003, Shneiderman and Plaisant 2006, Glier *et al* 2011, Sarkar and Chakrabarti 2011, Reich *et al* 2012). According to these references several assessment criteria have been outlined. These criteria are swiftness (1) (Glier *et al* 2011), simplicity (2) (Thiebaud 2003, Shneiderman and Plaisant 2006, Glier *et al* 2011), the capacity to be used stand-alone (3) (Thiebaud 2003), field adaptability (4) (Thiebaud 2003, Shneiderman and Plaisant 2006), group adaptability (5) (Thiebaud 2003, Shneiderman and Plaisant 2006) and the capacity to ease the following design stage (6) (Glier *et al* 2011). These criteria assess the required operating conditions for a given tool to deliver what it has been designed for, defining the practical criteria subset which will be used for all presented tools.

For each category, specific criteria were defined (see table 3 for a summary). These criteria aim to assess how one tool delivers what it has been designed for. These criteria define the theoretical criteria subset. In contrast to the practical criteria, the theoretical criteria are specific to the four respective categories of tools. The combination of the practical criteria with the specific theoretical ones was used for the assessment of the considered biomimetic toolset.

6.1.1. Analysis tools

Analysis tools should define the problem space (Newell and Simon 1972) by evaluating a situation exhaustively and precisely. They could also define the solution space (Newell and Simon 1972) by describing an ideal situation where the problem does not exist anymore. It is possible that they offer a way to prioritize underlying problems needed to be solved in order to reach the solution space (Jonassen 1997). Assessment criteria, defined in this work, are therefore the completeness (Ac) and the accuracy (Aa) of an analysis, identification of ideality (Id), and Prioritization (Pr).

6.1.2. Abstraction tools

Abstraction tools focus on generating models on different systemic levels. The purpose of these models is to ease the comparison of analogy between technology and biology, in our context, by increasing the level of abstractness (Chi *et al* 1981, Nagel *et al* 2010a) and reducing the amount of information taken into account (Chi *et al* 1981) while maintaining the contextual constraints as much as possible. Considered assessment criteria are modeling capacity (Mc), systemic levels integration (Sli), generalization capacity (Gc), information filtering (If), and constraints preservation (Cp).

6.1.3. Transfer tools

One of the challenges of biomimetics is the difficulties in communication between technologists and biologists (Helms *et al* 2009, Nagel *et al* 2010a). Their different backgrounds lead to divergent disciplinary or functional understanding of a concept (Dougherty 1992), whether due to perception (Dearborn and Simon 1958), languages (Tushman 1978), or 'thought styles' (Fleck 2012). Transfer tools are thus meant to precisely transpose concepts from biology to technology and vice versa.

They may handle different types of queries and provide outputs with different level of abstraction Considered assessment criteria are transposition precision (Tp) and direction (Di), query versatility (Qv), and consistency (Co).

6.1.4. Application tools

Application tools seek the concretization. They are the ones contextualizing back transposed models to produce embodiments. They are expected to lead to the identification of a small number of high inventiveness solutions (Savransky 2000) that solve the initial problem either by themselves or combined (Henderson and Clark 1990). Assessment criteria are therefore the knowledge enlargement (Ke), the uniqueness of solution (Uos), the inventiveness (Inv), and the modularization (M).

6.2. First study: workshops

The assessment of the biomimetic toolset has been performed with conditions as close as possible to an actual industrial implementation, involving experts in their working environment.

6.2.1. Context and protocol

Workshops were set to involve small groups of participants (i.e. five) and to last from one to two entire workdays. The first type of participants were the industrial representatives, acting as problem owners and setting up the industrial context for a given workshop. Workshops involved one industrial representative per workshop. The other two types of participants, were engineers and biologists. The engineers involved were researchers in design methodologies and innovation consultants, experts in problem-solving and design processes. Involved biologists were both renowned biomimetics/biomimicry lecturers and leading figures of their national bioinspiration related organization. Workshops involved two engineers and two biologists per workshops.

Due to the rarity of the population that was targeted, combined with the length of the workshops, only three workshops were implemented: two of them included an industrial partner and the third was carried out as a theoretical case study. Workshop participation redundancy reduced the total number of participants to 8.

The first workshop was held in collaboration with a French small-sized company working in the field of temporary accommodation for eco-tourism or one-time events. Studied products were spherical structures made out of a plastic film supported by an air flow generated through a compressor. The purpose of the workshop was to provide a way to integrate the temporary accommodation solution with less environmental impact. This led to the initial question: 'How can fluxes of energy be managed dynamically?'

The second workshop took place with a 3D-printing company. The selected topic was 'How to reduce the amount of input material without reducing structural strength?'

The last workshop, extrapolated from Azad *et al*'s (2015) and Malik *et al*'s (2014) work, focused on 'Designing a water bottle which harvests clean and non-salty water from the atmosphere for individual daily usage'. For the third workshop, no industrial representative was involved and has consequently been replaced by one of the authors to even the number of participants.

Facilitation was made by the two first authors of this work who are familiar with creative workshops in industrial environments. The participants received a methodological training depending on the tools' complexity and the overall existing knowledge of participants. The average training duration was approximately one to two hours per tool, conforming to the guidelines generated by their developers. Trainings were implemented according to the following procedure:

– General introduction on the theoretical background of the tool.
– Introduction to the means and purposes of the tool.
– Explanatory case study, performed by the facilitator.
– Pedagogical case study, performed by participants.

The achievement of the pedagogical case study allowed to ensure the proficiency of participants to a given tool. At the end of the training, tools were put to the test on the actual workshop case study. Instructions, such as templates and/or guidelines, were given to the participants.

Each tool was introduced individually through their specific training and afterwards they were used for the case study. Tools were sequentially implemented according to the unified process presented in figure 3. Introduction, training and application took place during the individual workshops.

Ultimately assessment sheets, illustrated in figure 4, combining theoretical and practical criteria listed in section 6.1, were distributed among participants in order to assess the tools.

6.2.2. Results

Though the workshops tackled different topics, the experimental conditions remained close. Results of workshops have thus been combined. The analysis of the results was performed by using the Wilcoxon Signed-Ranks Test.

Measurements showed a high degree of reliability (Cronbach's alpha range: 0.703–0.970), except for DANE and Domino which obtained questionable

Abstraction tool	
	What is your level of expertise with this specific tool? Very low ☐ - ☐ - ☐ - ☐ - ☐ Very high **What is your level of expertise with the described system?** Beginner ☐ - ☐ - ☐ - ☐ - ☐ Expert

Theoretical aspects

Modelling capacity: Capacity of the tool to model complex systems?
Not at all ☐ - ☐ - ☐ - ☐ Completely

Systemic levels integration: Capacity of the tool to integrate sub/super systems?
Very weak ☐ - ☐ - ☐ - ☐ Very strong

Information filtering: Capacity of the tool to filter information regarding its significance for the system understanding?
Very weak ☐ - ☐ - ☐ - ☐ Very strong

Generification capacity: Capacity of the tool to establish an access to the system in a generic way?
Very weak ☐ - ☐ - ☐ - ☐ Very strong

Constraints preservation: Capacity of the tool to maintain specific constraints with respect to the generated generic system?
Not at all ☐ - ☐ - ☐ - ☐ Completely

Practical aspects

Swiftness: Necessary time for the implementation of the tool?
Very long ☐ - ☐ - ☐ - ☐ Very short

Simplicity: Degree of complexity of the tool?
Need some specific training ☐ - ☐ - ☐ - ☐ Can be used instinctively

Stand-alone capacity: Capacity of the tool to be used as a stand-alone tool?
Can only be used within a global method ☐ - ☐ - ☐ - ☐ Can be used on its own

Field adaptability: Suitability of the tool to different fields?
Specific to one field ☐ - ☐ - ☐ - ☐ Completely adaptable

Group adaptability: Suitability of the tool to group composition?
It is mandatory to be either a single solver or a working group to properly use the tool
☐ - ☐ - ☐ - ☐ Can be used by single solvers or working groups with the same efficiency

Precedence: Capacity of the tool to facilitate the following step?
Not at all ☐ - ☐ - ☐ - ☐ provide the perfect entry point of the tool to come

Figure 4. Example of an assessment sheet (abstraction tool) used during the workshops.

correlations (Cronbach's $\alpha_{\text{DANE}} = 0.540$ and Cronbach's $\alpha_{\text{DOMINO}} = 0.491$).

Analysis tools. LP were assessed through the first workshop, the KARIM's version of LP (KLP), *S*-Curve and the Domino were assessed through the second workshop and the T-Chart through the third one. The grouped histogram in figure 5 introduces the result obtained across the assessed tools for each of the considered criteria, setting the means as the *x*-axis. Said results are compared, per criterion, to this overall mean in order to highlight their differences.

LP and KLP show low theoretical results with only Ideality (Id) scoring over 1. Results indicated that LP group adaptability (5) scores, Mdn = 2 were higher than KLP's. KLP appears to be relevant for many topics (Field adaptability's scores) and obtained Swiftness (1) scores, higher than LP ones.

The *S*-Curve analysis has shown strong capabilities in providing a complete analysis (Ac) of a given situation coupled with an idealized vision (Id). The fulfillment of these two criteria seems to allow designers to take the next step of the biomimetic process in a proper manner (Precedence's score (6)).

Unlike the LP or the *S*-Curve targeting to outline one or several strategic axes for an innovative process, the Domino focuses on the problem description. Through its results the domino differs from the prior analyzed analysis tools. Its theoretical impact has been recorded high on both the accuracy measurement (Aa) and the ability to prioritize (Pr). In view of its

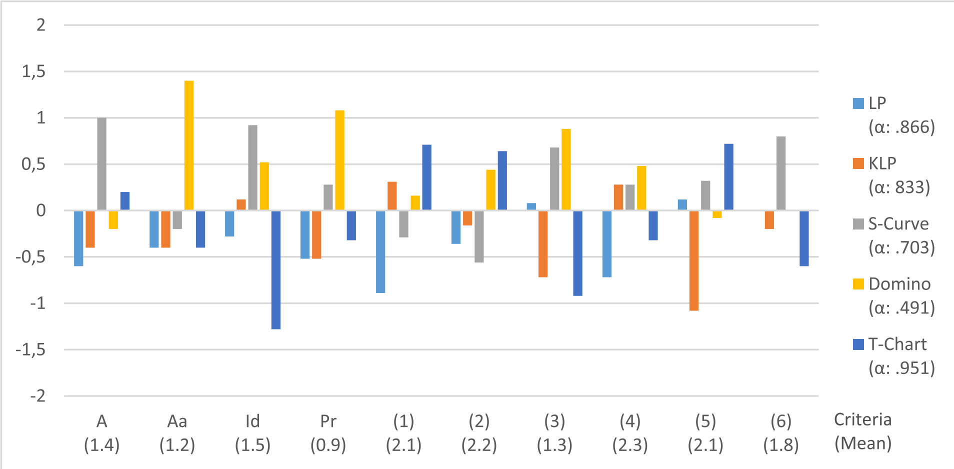

Figure 5. Workshops' analysis tools assessment results. With theoretical criteria Ac: analysis completeness; Aa: analysis accuracy; Id: identification of ideality; Pri: prioritization; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

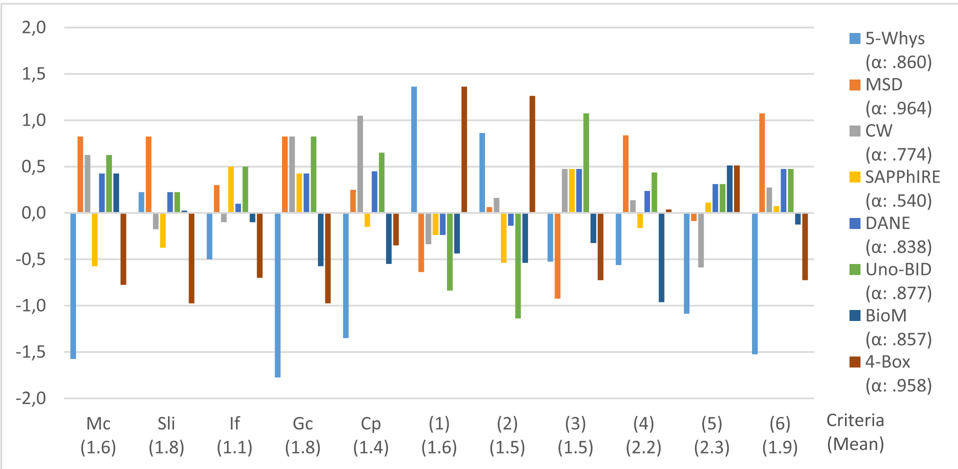

Figure 6. Workshops' abstraction tools assessment results. With theoretical criteria Mc: Modelling capacity; Sli: systemic levels integration; If: information filtering; Gc: generalization capacity; Cp: constraints preservation; and practical criteria 1: swiftness; 2: Simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

Simplicity (2), Swiftness (1) and Stand-alone capacity (3), the Domino seems to be a tool that one should consider while attempting to state appropriately a problem.

T-Chart, as an analysis tool, shows medium to low theoretical criteria scores. However, the tool scored high on its practical criteria. The Stand-alone capacity (3) is the only practical criteria to score low. Designers are thus suggested to pick the T-Chart's previous and/or subsequent tool in accordance with its use.

Abstraction tools. The 5-Whys and the MSD were assessed through the first workshop, the CW through the second one and DANE, SAPPhIRE representation, UnoBID, BioM and the 4-Box through the third one. The results are shown in figure 6.

5-Whys show low results on the theoretical criteria ($M_{5\text{-Whys}}$ range: 0–0.6), with only a better result on the sub/super system integration criterion (Sli). The tool's high score for Simplicity (2) and Swiftness (1) can hardly, in the context of the workshop, counterbalance its lack of theoretical efficiency.

The MSD showed a high capacity to deal with sub/super systemic levels (Sli). Its lower score (i.e. Information Filtering (IF)) still belongs to the top of abstraction tools. The tool scored a perfect Field Adaptability (4) and Precedence (6). On the other hand, MSD does not seem to be a stand-alone tool and therefore needs to be coupled with specific other tools to reach its full potential, making it relatively complex to use and difficult to implement.

The CW shows overall good theoretic abilities for modeling, except for its capacity to filter information. CW's highs are its capacity to maintain constraints (Cp) and its Generalization capacity (Ge). However, its use seems to require specific group typology (5) in order to be effective.

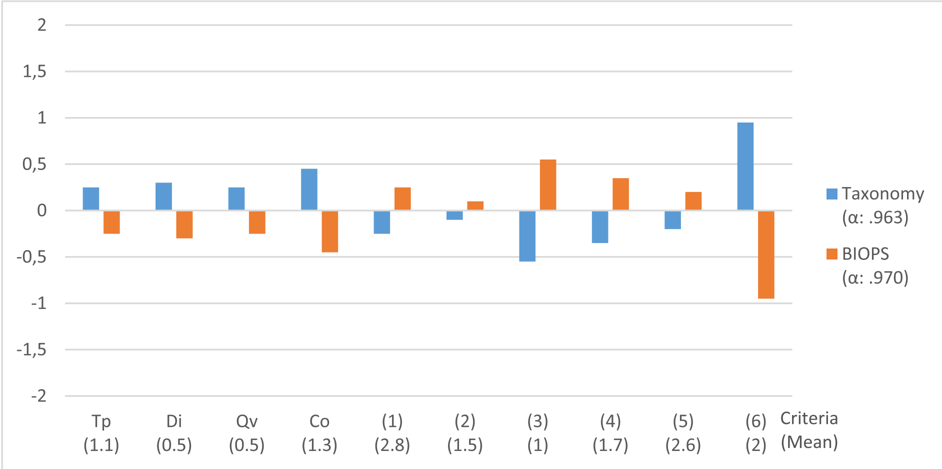

Figure 7. Workshops' transfer tools assessment results. With theoretical criteria Tp: transposition precision; Di: direction; Qv: query versatility; Co: consistency; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

The function-based modeling tools all scored high on theoretical criteria. Participants voiced their struggle at modeling a system involving several sub- steps with the SAPPhIRE representation, while DANE allowed them to do so without difficulty with its sequential state changes. Nevertheless, participants voiced the capacity of SAPPhIRE representation to highlight causal relations of the systems, leading to possible higher abstraction level modeling. Looking at the result, Uno-BID seems to achieve advantages of both SAPPhIRE representation and DANE with the downside of being difficult to handle and requiring time in order to be implemented.

The 4-Box showed medium to low theoretical scores, suggesting that other abstraction tools should be preferred to generate models. Results indicated that 4-Box ease of use (2) scores (Mdn = 3) were higher than MSD (Mdn = 2), CW (Mdn = 1) DANE (Mdn = 1) SAPPhire representation (Mdn = 1), UnoBID (Mdn = 0) and BioM; the same results indicated that 4-Box swiftness (1) scores (Mdn = 3) were significantly higher than MSD (Mdn = 2), CW (Mdn = 1) DANE (Mdn = 1) SAPPhire representation (Mdn = 1), UnoBID (Mdn = 1) and BioM (Mdn = 1). This makes, from our workshops results, the 4-Box the quickest and easiest tool, aside from the 5-Whys, to perform an abstraction. However due to the high interdependency of 4-Box and T-Chart (Stand-alone capacity score), the prior use of the 4-Box is recommended whenever T-Chart is implemented.

BioM results showed higher Modeling capacity (Mc), Mdn = 2, and higher Generalization capacity (Gc), Mdn = 1, than the 5-Whys (Mdn = 0 for Mc and Mdn = 0 for Gc). Therefore, BioM seems to outclass the 5-Whys when it comes to theoretical criteria. Compared with the results of function-based modeling tools BioM's theoretical and practical criteria do not differ statistically, except for the Generalization capacity (Gc), which appeared to be lower than Uno-BID's (Mdn = 3), SAPPhIRE representation's (Mdn = 2) and DANE's (Mdn = 2). Thus, BioM should be preferred under specific requirements (e.g. avoiding the relatively longer learning of functional modeling).

Transfer tools. The Taxonomy was assessed through both the first and the second workshop. BIOPS was assessed through the third workshop. The results are shown in figure 7.

BIOPS scores very low on every theoretical score and its practical scores are average to good. This seems to indicate that its use as a transfer tool in an industrial environment might be difficult. Its use could be contained to very specific operating conditions or needs related to one of its feature (e.g. Participants voiced its ability to perform queries into patent database). BIOPS obtained better Stand-alone capacity (3) results (Mdn = 1.5), than Taxonomy's (Mdn = 0).

The Taxonomy scored average to low on theoretical criteria. Its capacity to handle different types of queries input is especially low, meaning the input has to be formulated specifically before being transposed to the biological world. This underlying specificity is correlated by its low stand-alone score, leading to the use of a specific tool in order to perform adequately. Taxonomy obtained better Precedence (6) results (Mdn = 3), than BIOPS's (Mdn = 1).

Application tools. AskNature has been assessed through the first and the second workshop. Brainstorming has been assessed through the first workshop, and BIOPS and Bioniquity have been assessed through the third workshop. The results are shown in figure 8.

Due to its fundamentals, Brainstorming can hardly score high in the theoretical part. It has been designed to provide the largest quantity of concepts

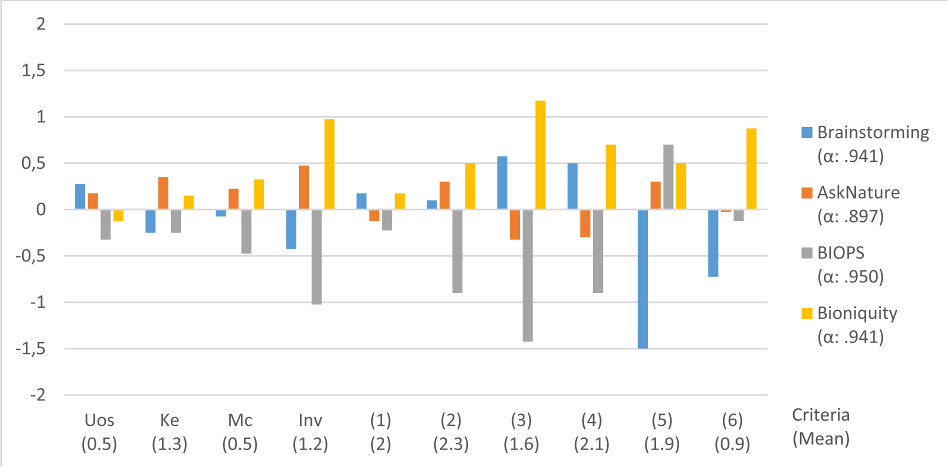

Figure 8. Workshops' application tools assessment results. With Uos: uniqueness of solution; Ke: knowledge enlargement; M: modularization; Inv: inventiveness; 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

(low score at pointing at unique solutions) while profiting from the embedded knowledge (i.e. few to no knowledge enlargement) of the gathered participants (groups are mandatory, i.e. low group adaptability). As expected, brainstorming scored poorly in these criteria, along with the two other theoretical ones. Unlike theoretical, brainstorming shows high scores in 'Swiftness (1)' and 'Simplicity (2)'. Brainstorming group adaptability (2) scores (Mdn = 0) were lower than all the other assessed application tools, i.e. BIOPS (Mdn = 3), Bioniquity (Mdn = 2) and AskNature (Mdn = 2). Brainstorming Inventiveness (Inv) scores (Mdn = 1) were also reported lower than Bioniquity's (Mdn = 2) and AskNature's (Mdn = 2).

AskNature showed a high enlargement capacity of the designers' knowledge while still being a quick and easy tool. Nonetheless AskNature was voiced as requiring the use of Taxonomy to reach its potential, and its Precedence (6) indicated that further work would be necessary to fulfill the step it has been designed for (i.e. identification of potential biological systems).

BIOPS, obtained in the overall limited scores with Inventiveness (Inv) scores, (Mdn = 0) even lower than Brainstorming's, (Mdn = 1); and Field adaptability (4) scores, (Mdn = 1), lower than Brainstorming's, (Mdn = 3), and Bioniquity, (Mdn = 3).

Bioniquity's Inventiveness (3) results (Mdn = 3), were higher than Brainstorming's (Mdn = 2) or BIOPS (Mdn = 0). Other significant differences were Precedence (6), Mdn = 2, and Stand-alone capacity (3), Mdn = 3, scoring respectively higher than Brainstorming on Precedence (6), Mdn = 1, and BIOPS on Precedence (6), Mdn = 0, and Stand-alone capacity, Mdn = 0. Bioniquity could, from the workshops results, be considered as a tool to generate potential disruptive inventions quickly and easily.

6.2.3. Conclusion of the workshops

The small amount both of workshops and participants are of relevant limitations and the lack of statistical data does not allow to draw any firm conclusions. However, certain tendencies have been outlined.

Abstraction tools tended to score high on the theoretical criteria, higher than the other categories of tools assessed. This tendency to provide well what these tools have been designed for, seems to come with a more limited user-friendly ability (i.e. simplicity and swiftness). However, these two trends do not seem to stand true for the 5-Whys and the 4-box. These tools presented good simplicity and swiftness scores combined with low theoretical criteria scores (combining theoretical scores leads to $M_{\text{5-whys}} = 0.52$, $SD_{\text{5-whys}} = 0.8$ and $M_{\text{4-Box}} = 0.76$, $SD_{\text{4-Box}} = 0.5$).

The main trends among transfer tools identified from the workshops is their low capacity to transpose both from technology to biology and from biology to technology (direction $M_{\text{Taxo,BIOPS}} < 1$). The fundamental principles of these tools show that they have mainly been thought to transpose from technology to biology. This observation constitutes a threat, as it could lead to a potential bottleneck when considering the whole process.

Results also showed that Transfer tools share low to medium Stand-alone capacity (Sla) ($M_{\text{Taxo,BIOPS}}$ range: 0.4–1.5). Taxonomy, which has been developed jointly with AskNature, and BIOPS, which is both a transfer and an application tool divided in two parts, leading to the consideration that these two tools might not be considered without their application counterpart. It is thus a combined Transfer-Application set of tools that should be selected to 'Transpose to biology' and 'Identify potential biological models', rather than two subsequent tools.

To strengthen the results of the workshops, the assessment would benefit from being put to trial with a

Table 4. Participants' subjective expertize on the assessed tools.

Tools	Mean	Standard deviation	Skewness	Kurtosis
TC	3.44	1.14	−0.327	−0.718
IFR	3.88	1.27	−0.797	−0.560
MSD	3.69	1.44	−0.733	−0.864
IP	3.46	1.12	−0.323	−0.788
Resources	3.47	1.35	−0.528	−0.967
Brainstorming	3.58	0.98	−0.452	0.143

larger audience, which was performed in a second study.

6.3. Second study: field survey

To assess the considered biomimetic toolset with a larger audience implies different conditions of assessment. The results of this second study should therefore show, to some extent, if the tendencies identified during the workshops are supported or undermined with a larger sample size.

6.3.1. Context and protocol

This second study makes it also possible to tackle the TRIZ theory which was yet to be investigated. The use of tools originating from TRIZ within biomimetic approaches has been promoted by a research group from the University of Bath (from which the consulting firm BioTRIZ derived), leading to the adaptation of some tools to the specificities of the biomimetic process (e.g. Bogatyreva *et al* 2003, Vincent *et al* 2005). Several tools from TRIZ have been presented as being of interest for biomimetics (Vincent and Mann 2002). The assessment of these five different tools (i.e. Technical Contradictions, IFR, MSD, Inventive Principles, Resources analysis) seized upon the 13th International Conference of the European TRIZ Association (TRIZ Future Conference 2013), which annually gathers TRIZ experts from across Europe.

Due to the context, training and implementation of actual case studies were unmanageable. Participants evaluated tools with questionnaires including the same list of criteria as during the workshops. As the precedence criteria (6) requires the following type of tools to be represented, brainstorming was added to the study. 86 participants, 51 industrial practitioners and 35 scientific researchers, answered the questionnaire. The average number of years of TRIZ experience over the participants was 7.05 (range: 1–16, SD $= 4.52$). The experience was non-normally distributed, with skewness of 0.41 (SE $= 0.26$) and kurtosis of -0.76 (SE $= 0.51$). The mean of participant's subjective expertize on TRIZ was 2.97 (SD $= 1.26$) out of 5 with skewness of -0.11 (SE $= 0.26$) and kurtosis of -0.46 (SE $= 0.51$). The subjective expertize of participants regarding the individual tools is presented in table 4.

6.3.2. Results

The Shapiro-Wilk W test has been used to evaluate each variable for normality. The majority of the observed distributions were identified as non-normal. The Wilcoxon Signed-Ranks Test was thus used as a non-parametric test for ordinal data. Cronbach's alphas (range: 0.815–0.971) showed a good to excellent internal consistency of the measurements.

Abstraction tools. The results of the abstraction tools' assessment are shown in figure 9.

Regarding the tested tools, MSD seems to be the best tool to model systems (Mc) ($\mathrm{Mdn_{MSD}} = 3$, $\mathrm{Mdn_{TC}} = 2$ and $\mathrm{Mdn_{IFR}} = 2$), combined with a better integration of super/sub-system levels (Sli) ($\mathrm{Mdn_{MSD}} = 3$, $\mathrm{Mdn_{TC}} = 2$ and $\mathrm{Mdn_{IFR}} = 2$). MSD however provides a lower level of abstraction (Gc) when compared to the other tools assessed ($\mathrm{Mdn_{MSD}} = 2, \mathrm{Mdn_{TC}} = 3$ and $\mathrm{Mdn_{IFR}} = 3$).

TC was assessed as offering a higher stand-alone capacity (3) compared with MSD and IFR ($\mathrm{Mdn_{Tc}} = 3, \mathrm{Mdn_{MSD}} = 2$ and $\mathrm{Mdn_{IFR}} = 2$).

IFR, compared to TC and MSD, seems to better preserve constraints (Cp) ($\mathrm{Mdn_{IFR}} = 2$, $\mathrm{Mdn_{TC}} = 2$ and $\mathrm{Mdn_{MSD}} = 2$), combined with a better adaptability regarding group composition (4) ($\mathrm{Mdn_{IFR}} = 3$, $\mathrm{Mdn_{TC}} = 2$ and $\mathrm{Mdn_{MSD}} = 2$). As a counterpart IFR seems to require more time than the two other tools to be implemented (1) ($\mathrm{Mdn_{IFR}} = 1$, $\mathrm{Mdn_{TC}} = 2$ and $\mathrm{Mdn_{MSD}} = 2$).

Transfer tools. The results of the transfer tools' assessment are shown in figure 10.

IP results showed higher transposition capacity (Tp) ($\mathrm{Mdn_{IP}} = 2$) than Resources ($\mathrm{Mdn_{Res}} = 1$) but lower stand-alone capacity (Sla) ($\mathrm{Mdn_{IP}} = 1$ and $\mathrm{Mdn_{Res}} = 2$ with $Z = 6.846$, $p = .000$). As IP are usually paired with Technical Contradiction, the stand-alone capacity results seem to confirm the necessity to combine them.

While offering less transposition capacity, Resources scored higher than TC on direction (Di) ($\mathrm{Mdn_{Res}} = 3$ and $\mathrm{Mdn_{Ip}} = 1$), consistency (Co) ($\mathrm{Mdn_{Res}} = 3$ and $\mathrm{Mdn_{IP}} = 1$) and group adaptability (5) ($\mathrm{Mdn_{Res}} = 3$ and $\mathrm{Mdn_{Ip}} = 2$ with $Z = 5{,}006$ $p = 0.000$).

Application tools. The results of the brainstorming's assessment are shown in figure 11.

Being the sole tool assessed in this category no direct comparison was possible. Brainstorming scored low on the theoretical criteria, while presenting intermediate to high scores on the practical criteria, except for group adaptability (5).

6.3.3. Conclusions of the field survey

The experiment has been run with a very specific target group; the International TRIZ Future Conference audience consisted of individuals who are at least initiated to TRIZ use, if not properly trained to it. For this reason, some of the practical criteria must be considered with caution, especially the ease of use.

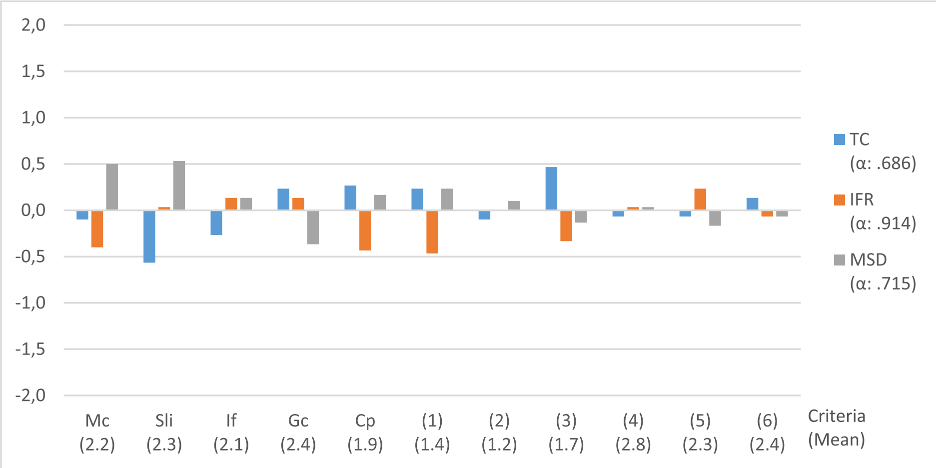

Figure 9. Field survey's abstraction tools assessment results. With Mc: modelling capacity; Sli: systemic levels integration; If: information filtering; Gc: generalization capacity; Cp: constraints preservation; 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

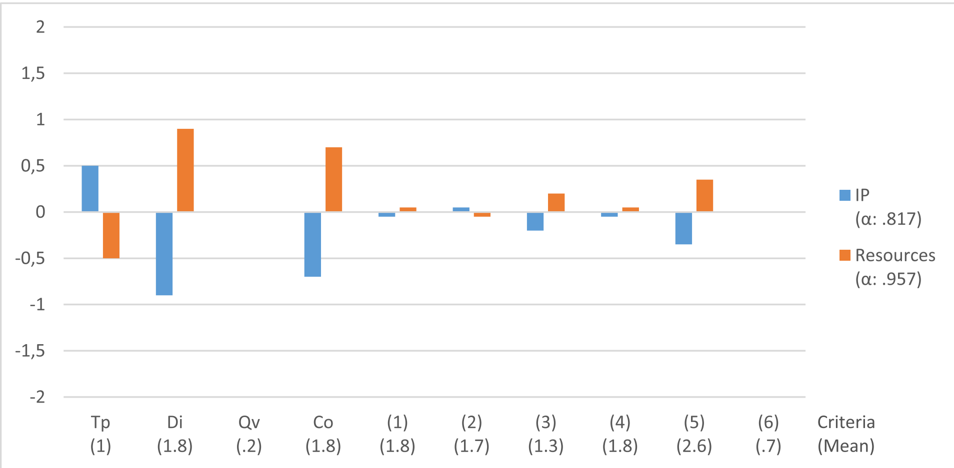

Figure 10. Field survey's transfer tools assessment results. With theoretical criteria Tp: yransposition precision; Di: direction; Qv: query Versatility; Co: consistency; and practical criteria 1: swiftness; 2: simplicity; 3: stand-alone capacity; 4: field adaptability; 5: group adaptability; 6: precedence.

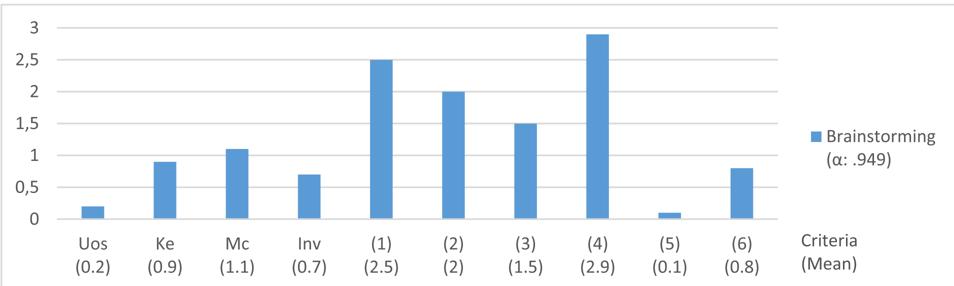

Figure 11. Field survey's application tools assessment results. With Uos: Uniqueness of solution; Ke: Knowledge enlargement; M: Modularization; Inv: Inventiveness; 1: Swiftness; 2: Simplicity; 3: Stand-alone capacity; 4: Field adaptability; 5: Group adaptability; 6: Precedence.

Results from the workshop and the field survey, cannot be compared directly, yet, some of the tools were assessed in both studies, i.e. MSD and Brainstorming. MSD shares the same overall profile (high scores in theoretical criteria with lower stand-alone capacity) and the same observation holds true for the brainstorming (fast and easy tool to implement with low theoretical criteria scores). As the main

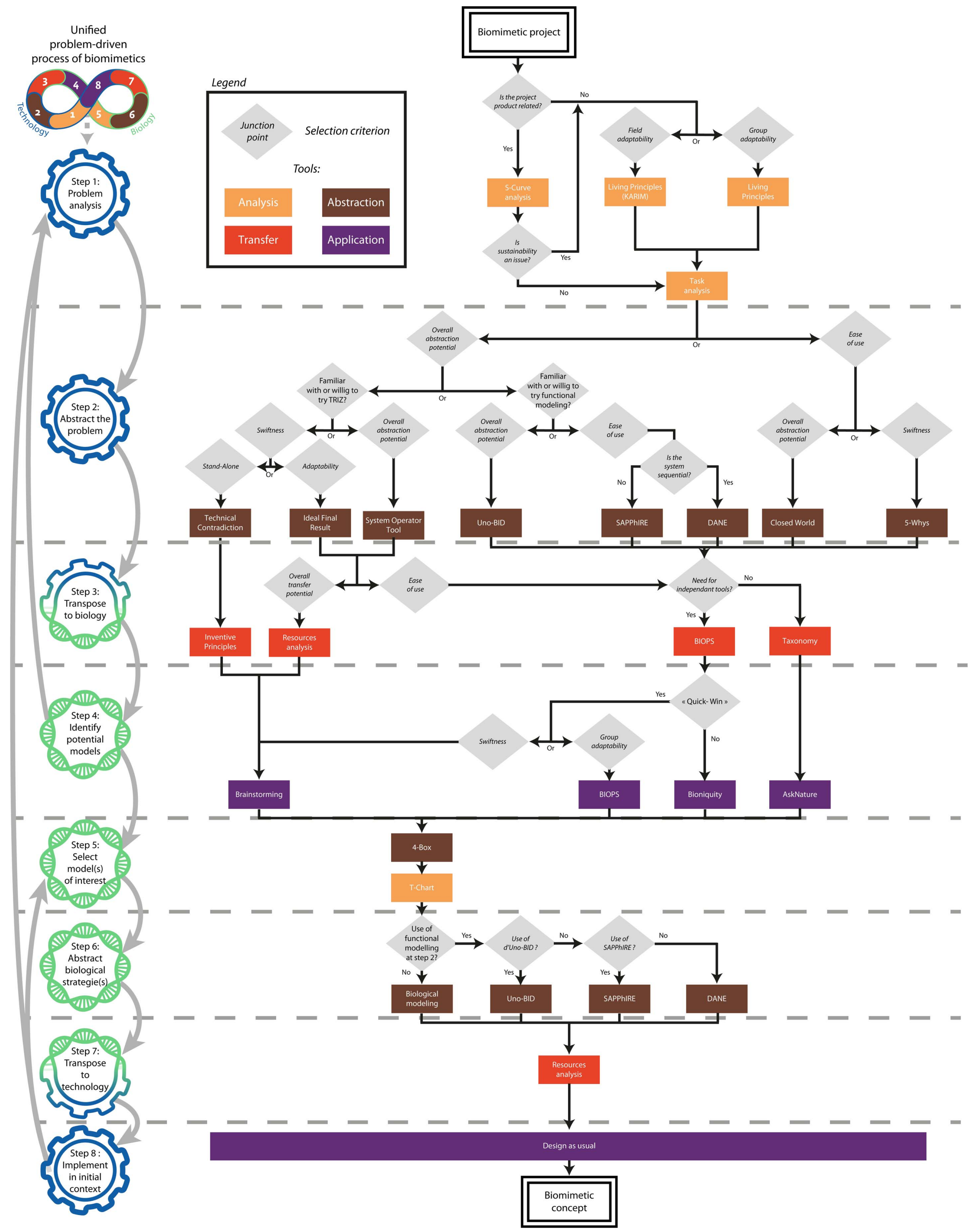

Figure 12. Problem-driven process of biomimetics utility tree.

conclusions drawn from the workshops remain identifiable through the field survey, it is possible to assume that the results from the workshop studies provide some form of representational view.

7. Building a problem-driven biomimetic utility tree

To ease the holistic understanding of the conclusions and tendencies drawn from the assessments, a visualized presentation of the results is proposed. The utility tree presented in figure 12 combines both the unified problem-driven process model of biomimetics (figure 3) and the assessed tools mapped to it (table 1).

Each junction point of the tree is either defined by assessment criteria used during the case studies, characteristics of the project or experience and preferences of the solvers. Tools are distinguished according to their experimental results (i.e. for the considered criteria, or voiced during the case study).

The purpose of such a utility tree is to guide practitioners through the biomimetic process model and its tools. Practitioners are asked to answer questions at the junction points in order to select a tool. This way they can build their own biomimetic process based on the current experimental results. It is necessary to mention that none of the listed steps or tools are mandatory; users can enter and/or exit at any junction point.

The use of the tree can therefore be adapted to support their way through the biomimetic process. Following the entire biomimetic utility tree should result in a bioinspired design, a biomimetic product fulfilling the criteria of ISO TC 266 (2015) Biomimetics.

As mentioned before, the unified problem-driven process model of biomimetics requires knowledge both from biology and technology. The same holds true for the utility tree as biologists are needed at several steps, especially if the offered tools do not provide a deep understanding of biology. As the utility tree is more a framework than a mandatory route to follow, users should decide individually when to look for external expertize. The role of biologists indicated in the utility tree is highlighted when it is considered to be mandatory in most cases. Even at earlier steps their contribution may be needed and is emphasized (Snell-Rood 2016).

The utility tree may be adapted to individual needs as each problem or design task has its specificities. After choosing a way through the utility tree, practitioners need to be familiar with the set of tools referring to the chosen way through the utility tree.

At present, the utility tree consists of a subset of existing tools and shall therefore not be considered to be finalized. It is rather a first version of a guideline through the process which needs to be used for data collection from various cases. We consider it to be a starting point for a broad discussion and it is highly appreciated if the utility tree is used for case studies from different fields. This expected future data, which could be gathered collaboratively, could provide an initial more robust version.

8. Conclusion

The evolution of biomimetics in the near future still requires a lot of research. The work presented in this paper can be a starting point for a systematic advancement of the process of biomimetics, especially for practitioners from the industrial sector.

The assessment of the biomimetic tools led to the premise of a utility tree which, once finalized, could enable practitioners to implement the process of biomimetics in their own context. It is a first attempt to set up a methodological process that has been lacking for a long time. It focuses on the application of biomimetics as a process and provides potential users with the 'how to do biomimetics' practically.

The establishment of this first iteration of the utility tree offers a basic architecture which can be strengthened through the addition of experimental data gained from studies with a broader range of users (with less expertized profiles). This new set of assessment workshops constitutes an ongoing study lead by the authors. Furthermore, comparative case studies, the addition of more tools and the identification of challenges during the use of the utility tree will improve the utility tree towards a robust version.

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applied sciences

Article

What Do We Learn from Good Practices of Biologically Inspired Design in Innovation?

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Abstract: Biologically inspired design (BID) is an emerging field of research with increasing achievements in engineering for design and problem solving. Its economic, societal, and ecological impact is considered to be significant. However, the number of existing products and success stories is still limited when compared to the knowledge that is available from biology and BID research. This article describes success factors for BID solutions, from the design process to the commercialization process, based on case studies and market analyses of biologically inspired products. Furthermore, the paper presents aspects of an effective knowledge transfer from science to industrial application, based on interviews with industrial partners. The accessibility of the methodological approach has led to promising advances in BID in practice. The findings can be used to increase the number of success stories by providing key steps toward the implementation and commercialization of BID products, and to point out necessary fields of cooperative research.

Keywords: biomimetics; biologically inspired design; biomimicry; industrial application; innovation; case studies; best practice; process and tools; sustainability

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1. Introduction

Learning from nature has a long history with a well-known potential for innovation and many success stories [1–5]. Ongoing discoveries in nature, arising fields of application as well as the challenge to transform learning from nature into a robust, repeatable, and scalable methodology [6] keep it an emerging field of research [1,7]. Several approaches and definitions exist [8,9], which describe learning from nature to solve technological or practical problems. Biologically inspired design (BID) will be used in this article because we understand BID as an overarching term which describes the knowledge transfer from biology to technology in general. This affords us the opportunity to include a broad range of approaches related to learning from nature, with very limited exclusion [5]. We will give a first insight into examples of good practices with associated success stories, selected for our assessment of the ease of transfer to other approaches. When necessary, we will also use the terms biomimetics or biomimicry in particular, to respect the underlying definitions, motivations, and differences [5,10].

Research about BID, its definition, and methodology is ongoing and sometimes controversial [6,8,11]. Nevertheless, it is clear that learning from nature is a dominant paradigm [1] and as such it can be used and implemented in practice in various ways, for instance by connecting it with design approaches or by considering it a scientific discipline itself [5,7]. Implementing BID in practice offers a potential to generate optimized solutions combined with the potential to address sustainability as shown for instance with air-retaining surfaces which lead to drag reduction and, as a consequence, a reduced fuel consumption [12]. The topic of sustainability in the context of BID [2,8,13–15] as well as the limitations of transferring knowledge from biological systems to technological application [16] need separate analysis, and the reader is referred to the indicated literature.

The process of BID is well described in the literature and various research programs focus on the efficiency of the process in practice, developing methodologies, tools, and processes [6,11,17]. As BID is a complex and multidimensional process, which involves several disciplines, the development of concepts or products in BID can be challenging to carry out, and in addition, the steps of commercialization are particularly challenging.

BID can be understood as a methodology (which can be used for product optimization), as human-centered design, to a systems thinking approach. It can be closely connected to the innovation process and as such be used for new developments, the rethinking of existing products, or idea generation. In addition, BID can enhance the ideation process in conjunction with the use of strategic foresight and design thinking. Once it leads to a radical (disruptive) innovation, it can have a significant impact on a market, on the economic activity of companies in that market, or potentially lead to the creation of new markets. BID can augment entrepreneurial innovation processes by guiding a designer from a nature-inspired idea to a proof of concept, to a successful solution (product), to an innovation, or even to the establishment of a new company and/or industry, as seen with the development of the hook-and-loop-system VELCRO® [18] or with the surface technologies Sharklet [19].

However, though the potential of BID solutions for innovation is well known [1,20], it does not necessarily mean that these ideas reach the market and unfold their theoretic potential. For example, the discovery of the self-cleaning properties of the lotus plant [21] was a disruptive new paradigm, however the application in products did not have the respective impact on the market (yet), such that every thinkable product, for which self-cleaning properties were desirable, contains such a surface. Furthermore, comprehensive and well-established success stories are either poorly communicated or do not exist, as the number of known products inspired by nature on the market is small [22]. The BioM Innovation Database introduced the first worldwide analysis of products, named as the result of the BID process [22]. Referring to the available knowledge from biology [23] and its emerging amount of scientific literature [1,7], the potential for product development and innovation is very high. However, the number of documented products on the market as shown in the BioM Innovation Database is comparably low, with n = 379 cases. This discrepancy between theory and practice has various reasons, such as challenges of the BID methodology [17,24] or its implementation in practice [11]. Therefore, with this article we highlight a few aspects to be considered in future projects and research in order to help tap the potential of BID.

Biologically Inspired Design in Innovation

In this article, we make a first connection between BID and various aspects of the general innovation process. On the one hand, we aim to indicate similarities so that we can learn from other disciplines and approaches for the future development of BID as a repeatable methodology. On the other hand, we highlight specificities and challenges whenever possible. This direction of the article raises further research questions which will be discussed at the end of this article.

By definition, an innovation needs to reach the market; it is not merely a new technology or invention [25]. The same holds true for BID once it is considered to be an innovation strategy [5,26] or part of the innovation process, in general, starting with idea generation and ending with commercialization. Figure 1 shows the three main phases of the innovation process [27], matched with the eight steps of the unified problem-driven process of biomimetics, as described by Fayemi et al. [11]. This highlights that BID can be understood and performed like a general innovation or problem-solving process [28]. However, in each phase specific tasks must be performed, tools can be used [11,17,28,29], and unique challenges must be overcome [24,30–32].

If we have a look at the three main phases of the innovation process (Figure 1), most research in the context of BID has focused on the first two phases. In particular, the focus has been on the contribution of BID to idea generation and to the development of biologically inspired solutions. In this context, several studies analyzed cases of BID, for instance the motivation for development [33], how to classify [8] or assess the solutions, for example, in terms of sustainability [14,15], or the general success of development [2,22]. Based on the BioM Innovation Database [22], 70% of the BioM products did not make it to the marketing phase, as they were still in development, a concept, or already discontinued. As phase 3 of the innovation process was little researched in the context of BID, we analyzed steps in the transition from a BID concept to a product on the market, based on case studies and the BioM Innovation Database [22]. The phase "Idea & validation", as shown in Figure 1, could be performed prior to idea generation in order to validate the use of BID in innovation processes. In doing so, first steps of the market analysis are performed early in the development and help to facilitate phase 3, as important questions for the commercialization are addressed early in BID projects. In addition, BID could benefit from using general innovation processes, such as a structured management process and the use of minimum viable products (MVP). It is still necessary to analyze whether processes would be of benefit to BID and the ones to choose.

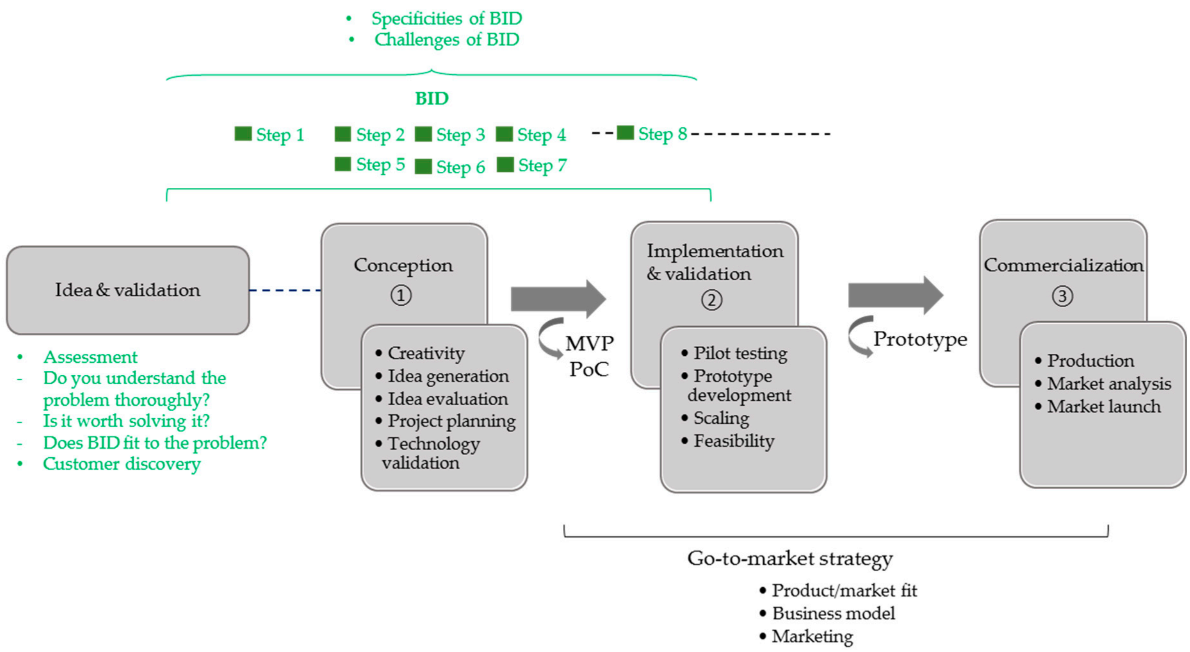

Figure 1. Phases of the innovation process linked to the eight steps of the biologically inspired design (BID) process as described with the unified problem-driven approach of biomimetics by Fayemi et al. [11]. ①, ②, and ③ indicate the main phases of a simplified innovation process. The eight steps of BID include specific tasks which must be performed and are linked to commonly known challenges [24,30–32] which must be overcome. BID: Biologically inspired design; MVP: Minimum viable product; PoC: Proof of Concept.

Various types of innovation can be distinguished, from routine innovation, incremental improvements, to disruptive or fundamental innovation [25,27]. Interestingly, BID can contribute to each type of innovation as it can inspire:

- to improve existing products, for example, noise reduction and vibration of aviation wings inspired by owls [34,35],
- to develop new products, as seen for example with the development of artificial attachment devices based on the dry adhesion of the gecko [36],
- or to transpose a scientific discovery to an application, as seen with the self-cleaning properties of the lotus plant, which also led to a true paradigm shift [21].

As such, the use of BID in innovation management can decrease the number of attempts to reach a certain level of innovation by using the solution space of nature for knowledge transfer.

As shown in Table 1, some studies suggest that about ten attempts are needed to achieve an obvious, conventional solution to a problem within its own field and with known methodologies [37,38]. Each following step toward a higher level of invention, based on the novelty, raises the number of attempts to the power of ten, so that for a discovery of a new scientific phenomenon, which leads to a paradigm shift, more than 100,000 attempts are necessary [37,38]. One can imagine that problem solving becomes a time consuming and difficult challenge, so that methods of generating novel and useful ideas are needed. BID can be considered to be such a methodology and to offer a design space with proven solutions with a defined level of performance. Like other creativity techniques, it could therefore be considered to—if desired—decrease the number of attempts; this offers the chance for breakthrough innovation, makes use of a systematic knowledge transfer, and can turn serendipity into a means of designing solutions. Still, the process of actually doing it remains challenging.

Table 1. Level of invention and number of trials.

Level of Invention	Number of Trials	Percentage of Patents
Apparent: Established solutions; well-known and readily accessible (e.g., reinforcing a wall by making it thicker)	1–10	35
Improvement: Existing system improved, usually with some compromise (e.g., a new electronic device based on already existing components)	10–100	42
Invention within paradigm: A concept for a new generation of an existing system (e.g., automatic transmission)	100–1000	19
Invention outside paradigm: A new concept for performing the primary function of an existing system (e.g., X-ray machine, CD-ROM, RF receiver)	1000–100,000	4
Discovery: Pioneering invention of an essentially new system (e.g. X-rays, laser, radio)	more than 100,000	0.3

Based on [37,39,40].

Regarding its origin, BID can be performed a) in academia, b) in collaboration between academia and industry, or c) in industry for the development or improvement of existing products. When BID is performed in academia and the research is mature enough to make viable products, the collaboration between academia and industry becomes increasingly important in order to implement the concept from lab to application. Alternatively, the academic research could be developed further by an academic spin-off, as seen for instance with the technological spider silk [41]. The collaboration between academia and industry can also be due to a market pull, where industry needs solutions for existing problems and seeks the collaboration with respective experts from academia, as shown for instance with the development of a self-sharpening knife [42]. Examples for the performance of BID in industry are manifold, from using BID as a problem-solving strategy as part of the overall product development process (e.g., as seen with the development of paintings [43] or fan systems [44]) to an innovation strategy, such as the so-called bionic learning network of FESTO AG [45].

The general challenges of innovation, as well as the gap between academic research and industry [46], are sometimes referred to as the "valley of death", as shown in Figure 2. The aforementioned challenging aspect of carrying out BID becomes even more challenging, once it becomes necessary as well to perform the steps required to overcome the "valley of death".

In addition, best practice in BID includes a successful transfer of knowledge from biology to technology, with the abstraction of the principle and its application [3,5,8,20,22]. These steps define the three criteria of a true biomimetic development, namely, 1) a function analysis of a biological system has been made, 2) the biological system has been abstracted into a model, and 3) this model has been transferred and applied to design the product [5]. In order to call an innovation based on BID "biomimetic", these three criteria must be fulfilled.

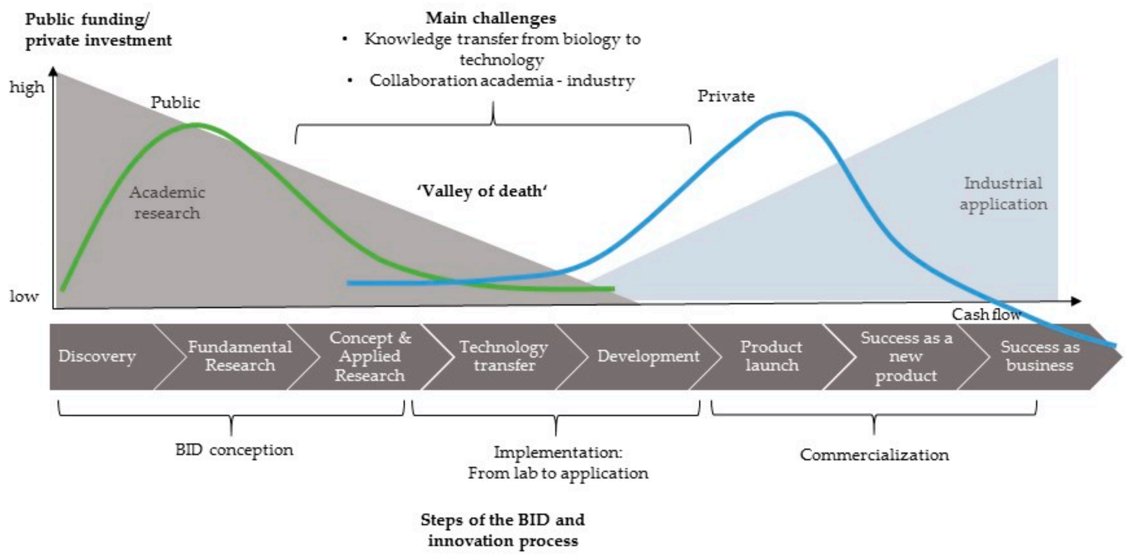

Figure 2. The "valley of death" in innovation and the context of the simplified BID process. Based on and adapted from [46,47]. BID: Biologically inspired design.

A BID development can occur at the level of a product, a process, or a practical problem [5] or it can address a societal challenge such as sustainability [33,48]. The contribution of BID to sustainability is an important branch of research [5,8,14] that deserves separate analysis. We therefore address it only when needed in the context of this discussion. Otherwise, we do not make a differentiation in the analyzed cases. Once the result of BID has reached the market, it represents an example of a "good practice" biologically inspired innovation.

The challenges faced in the "valley of death" hold true for any kind of development, so we analyzed its relevance in the BID process. On the one hand, BID faces the same challenges as general innovation processes, such as the transition from a concept to a viable product. On the other hand, BID faces additional challenges, deepening the "valley of death". Among others, the knowledge transfer from biology to technology is challenging, as phenomena in biology and their transferability must be understood in detail. Moreover, the transfer from academic research to industrial application is also challenging, as you must convince potential users with your idea that was inspired by nature. We assume that the lack of BID's real impact with regard to the number of successful cases as well as its economic and ecological impact is the general lack of implementation, the difficulties during the research and development process, and the lack of a viable commercialization strategy including the availability of funding. The research phase in BID is specifically challenging [2]requiring, for example, an intensive research and a deep understanding of biological systems or the abstraction of complex biological phenomena [2]. Additionally, the transfer process of knowledge from biology to technology may differ between projects and can impact the overall innovation process [2]. The chosen level of abstraction will define how much time and money must be invested. Moreover, the gap between discovery phase and commercialization is strenuous and filled with many obstacles and hurdles. Part of the problem is that you cannot really commercialize a discovery, you can only commercialize a viable product. The truth is that the innovation process is not a single event, but a process of discovery, design, and development. To bring a breakthrough discovery to market, one first needs to identify a problem it can solve and connect to researchers who can design it into a viable solution to the problem.

These pitfalls are well known within a traditional innovation context, where about 25% of innovation projects are discontinued, 30% experience serious delays, 35% will commercially fail, leading to an overall 10% rate of complete success [49–51]. Information about the success of developments based on BID is limited and little data is available in order to make a comparison with the traditional innovation process. In addition, the impact of integrating biological knowledge into the innovation process must be evaluated, but no clear methodology is available, yet. However, based on the BioM Innovation Database [22], it can be seen that 31% of the developments based on BID were commercially available, even though no information is available about the success of these products. This means that 69% of the ideas, which were considered to be of value, did not make it to a viable product.

As a result, working toward a deeper understanding of the BID process—from idea to market, including assessments—will increase its implementation and support the development of biologically inspired solutions in the future. Design ideas without execution with a strong technical and business validation will generate unsuccessful outcomes and discourage innovators. True competitive advantage comes from those that can take an idea and turn it into a real innovation that has an impact, be it societal, environmental, or economic.

Therefore, we focus on key aspects of BID's success that are important for the implementation of concepts and their commercialization (Figure 1). The simplified steps encompass several more tasks and activities which include the BID process itself with its challenges [24,30–32,52,53] and tasks to perform [11,54]. The results of this article will help to 1) better understand the BID process and 2) assist designers in overcoming the "valley of death" for BID solutions and therefore pave the way toward a more successful commercialization process. We aim to give recommendations for the successful implementation of BID solutions, to help industry to implement BID in their own context, to increase the impact of BID in research, development and innovation, and to combine economic growth and sustainable and responsible innovation [55].

2. Materials and Methods

Results presented in this article are based on interviews and business case studies.

First, the BioM Innovation Database (n = 379) and associated interviews with inventors of the respective products were analyzed (n = 69) [22]. The number of interviews is lower than the number of cases available. This is due to confidentiality or lack of information available or given in the interviews. The database was gradually filtered, which means that only the cases that provided a full set of data with regard to a certain topic were analyzed and compared. Therefore, results encompass various subsets of the database.

Second, an analysis of 14 business case studies was performed at the University of California, San Diego. The case studies were identified through scientific and business literatures and subject matter experts. The data were accessed through a variety of sources, such as interviews, company news and financial information, government and economic data as well as industry reports. The cases were analyzed in order to understand the commercialization process for BID solutions, to identify go-to-market strategies, and to examine funding strategies. The cases came from seven industry sectors: Energy, Water, Healthcare & Medical Devices, IT & Telecommunication, Built Environment, Manufacturing, and Transportation. The cases can be referenced as biomimicry cases, as its underlying methodology was used [56,57].

3. Results and Discussion

3.1. Innovation and Commercialization Process / Steps Toward Commercialization

Figure 3 shows the development of BID concepts and products in the years 1970–2012, as summarized in the BioM Innovation Database [22]. As data about the year of development were only available for a subset of the cases, 94 concepts were analyzed.

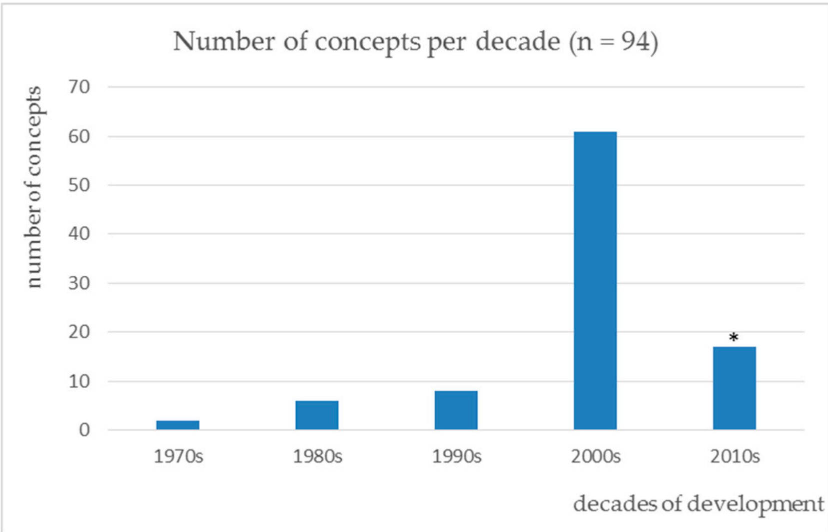

Figure 3. Number of BID concepts per decade from 1970 to 2012 (n = 94). *: The asterisk indicates that the underlying data cover only the first two years of the 2010s. Newly developed concepts and products in the years 2013–2019 must be added once they are researched.

The development of BID concepts, based on data from 1970 to 2012 [22], had an increasing trend over the last decades with the highest number of documented cases so far in the 2000s. It will be interesting to see how this trend developed during this ending decade and how it will in the future. As indicated for the scientific literature, the growth of knowledge in BID is still ongoing [1,2,4,7]. Moreover, various new fields of application for BID may arise, as the approach can be shifted to systemic and organizational approaches, rather than products and processes alone [4]. In addition, a stronger connection to other topics and disciplines, such as innovation management, circular economy, regenerative design, cradle-to-cradle design, sustainability, or ecosystem services, may expand the perspective of BID into the future.

From the products listed in the BioM Innovation Database [22], ~31% were commercially available, ~58% were in development (prototype phase), ~8% were unpatented concepts, and ~2% were discontinued. Figure 4 summarizes the output of 95 cases from the BioM Innovation Database, with regard to resulting patents.

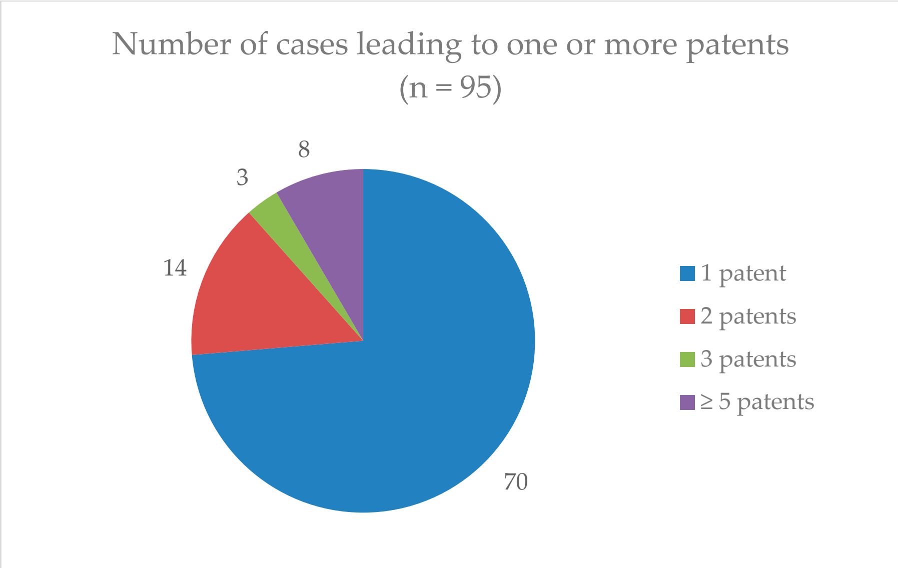

Figure 4. Number of patents per BID concept based on the BioM Innovation database [22]. As shown, 70 BID concepts led to a single patent (74%), 14 to two patents (15%), 3 to three patents (3%), and 8 to five or more patents (8%).

As patents are only accepted if it is demonstrated that the concept is new, creative, and feasible, the results support the notion that BID has the potential to lead to various kinds of innovation. Not only incremental but also disruptive innovation is possible. As biological systems are not allowed to be patented, patenting is also a way to standardize the biomimetic aspect of BID, because one must abstract the biological principle and describe in detail its application to technology to obtain the patent. In this context, some work still must be done to present BID as a well-structured methodology for product development in companies. All aspects along the value chain for innovation, from the process itself to its management and successful implementation, commercialization, and IP protection, can potentially be revisited, in order to build the foundation for a clear approach. Some of these topics are part of ongoing research, addressing for instance the relationship between inventions, patents, and bio-inspiration.

The commercialization process is one of the key aspects of BID innovations. Figure 5 shows the minimum, maximum, and median time that was needed to develop a prototype and then enter the market, based on cases from the BioM Innovation Database [22], which provided full information about the overall process. The analyzed 33 cases can be distinguished in accordance with their fields of application [2], namely, (1) surfaces (n = 1); (2) evolutionary strategies & optimization (n = 5); (3) communication & sensory systems (n = 2); (4) materials, structures & lightweight (n = 19); (5) architecture & design (n = 5); and (6) fluid & aero dynamics (n = 1). Although the development process in different industry sectors and application fields varies, requiring separate analyses, we combined the cases, because the number of cases in various groups was too small to provide meaningful results. In the future, it will be interesting to compare subsets of cases from different fields of application to see whether there are sectors which have longer or shorter times of development. In addition, it will be interesting to see whether and how BID development times differ from those in standard innovation processes.

The overall commercialization process lasted 1–23 years in total, with an average duration of approximately 6 years. Phase 1 (concept to prototype) had an average duration of approximately 1.9 years and phase 2 (prototype to market), of approximately 3.7 years. The analysis of the 14 business case studies showed an average time-to-market of approximately 9 years.

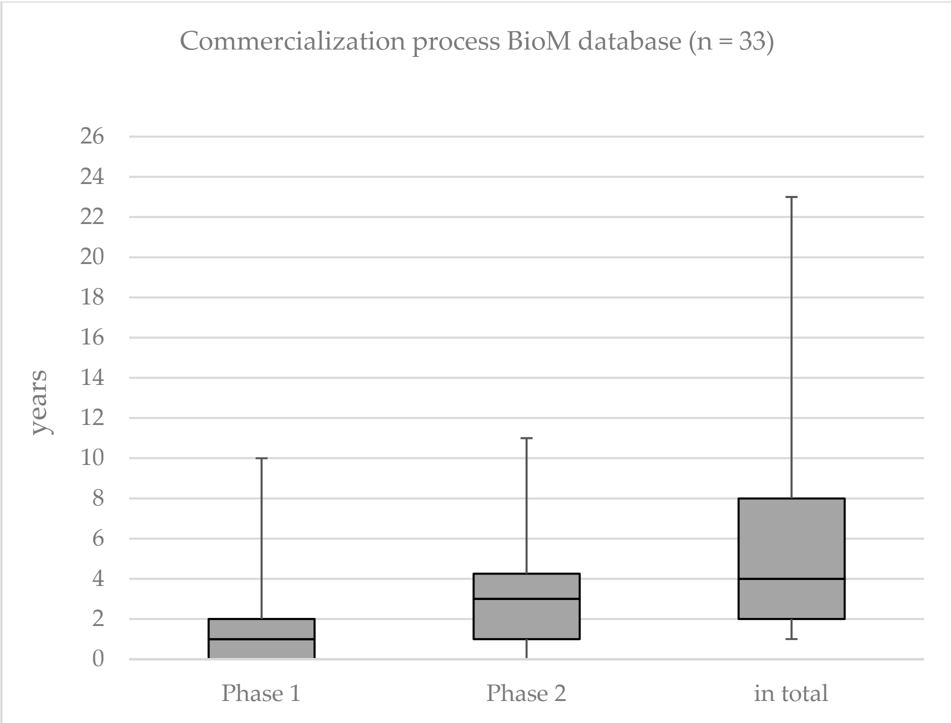

Figure 5. Duration of the commercialization of 33 BID products in years. Phase 1: concept to prototype; phase 2: prototype to market.

The time for developments in BID varies with regard to the intensity of research that is necessary to understand the biology in detail, to abstract the underlying principle of a biological phenomenon, and to transfer it successfully to technology (phase 1). Furthermore, the development from a prototype to a viable product (phase 2) is likely more time-consuming. The common problem of up-scaling may be specifically demanding in BID, as seen for instance with the development of biologically inspired hierarchical structures in material sciences [58]. In such cases, the development process may require phases of reverse engineering and iterative loops. As each project in BID is unique, a deeper analysis of more cases will be needed in the future to make more precise differentiations and comparisons.

However, the development times reflect certain barriers that are often raised by industry regarding why BID may not be of interest to them. The time needed to develop a viable prototype or a final product seems to be too long for projects in industry that need a solution to an existing problem. This holds true especially for small- and medium-sized enterprises (SME) which often do not have a specific innovation subunit with the budget and time for future developments. Of course, every development takes time and needs money, and if solution-finding were easy, no creativity technique or innovation management would be necessary. However, BID has specific challenges regarding its process, as mentioned before, and the challenge "to use the paradigm to address increasing numbers of real problems that translate into real products in the market" [6] requires much more work. Therefore, BID could be used in various ways, for instance to generate new ideas, coming from a solution space that had not yet been considered, so that first insights of its potential can be communicated to people of interest and that first (sub) results are gained more quickly. In addition, the abstraction of the problem, that must be solved, can be defined on various levels and therefore the abstraction offers chances to estimate required efforts and time. Of course, once a phenomenon of nature is identified and must be understood in detail, time is required to carry out the appropriate research. In this context, companies must be well aware that BID is not a shortcut to ready-to-use solutions, but it can offer various benefits for the company. As such, if a company is willing to invest time and money, BID offers the potential for not only incremental, but also, potentially, disruptive innovation. In addition, new markets can be entered once a phenomenon of nature is well understood and it becomes possible to transfer it to technology. This raises the question about how BID projects can be successfully integrated into business models and how they can be managed effectively.

In order to find out which process of BID (solution-based or problem-driven) was used for the development of BID products, we analyzed the BioM Innovation Database with regard to the time needed to develop prototypes and to enter the market of the respective cases, as summarized in Table 2. Most of the products, documented in the BioM innovation Database, were developed using the solution-based approach in contrast to the problem-driven approach.

Table 2. Time to develop prototypes and products for commercialization, based on the two approaches of BID.

Process	Number of Cases	Minimum Duration (Years)	Maximum Duration (Years)	Average Duration (Years)
Phase 1: concept to prototype				
problem-driven (Design to Biology)	16	same year as concept	10	1.6
solution-based (Biology to Design)	29	same year as concept	10	2.1
Phase 2: prototype to commercialization				
problem-driven (Design to Biology)	8	1	11	3.3
solution-based (Biology to Design)	15	same year as prototype	11	4
Phase: concept to commercialization				
problem-driven (Design to Biology)	8	1	13	5.5
solution-based (Biology to Design)	15	1	23	6.8

The results about the duration of the development of a prototype or a product to enter the market show that there is no significant difference. On average, both approaches needed approximately 1.9 years to develop a prototype, and an additional 3.6 years to enter the market. That there is no significant difference between both approaches may be due to the fact that some of the individual steps and tasks to be done in both development processes are similar, even though they have a different order and intensity.

Once the process with its steps of BID is well described and available to practitioners, it can help to increase the implementation and success rate, as it can be communicated clearly what BID projects resemble, what is needed in order to succeed, and where the difficulties arise. Each BID project is unique, but we were able to identify and analyze common challenges related to BID projects that were communicated in the interviews.

3.2. Challenges of the Process and Barriers to Market Entry

The BioM Innovation Database case studies as well as the 14 business cases were analyzed with regard to documented challenges. Based on these findings, we defined resulting effects and key factors for success, shown in Table 3.

In the interviews resulting from the BioM Innovation Database, inventors were asked about challenges arising from interdisciplinary teamwork in particular. Interdisciplinary teamwork refers mainly to the collaboration of biologists and engineers from various disciplines (e.g., material engineering and biomechanics). From the 56 interviews which provided information to this question, 75% answered that there were no challenges arising, and they emphasized the benefit of interdisciplinary work. However, they mentioned that common sense and open-mindedness are a necessary foundation for collaboration. For the 25% who noticed challenges, it was mostly due to communication and translation across disciplines. This indicates that knowledge translation and transfer (KTT) is a constant demand in BID that also requires an interdisciplinary language. One interesting finding was that it could be very difficult to convince people of a new idea that was inspired by nature as it might not fit into technology state-of-the-art. It might also be difficult to find partners. In addition, the need to work with experts to acquire a deep understanding of biology was emphasized. This indicates that several obstacles in BID may be due to its disruptive nature, which on the other hand justifies the investment and endurance needed.

Table 3. Challenges, effects, and key factors of success based on reports from developers in BID projects. KTT: knowledge translation and transfer; IP: intellectual property.

Challenges	Effect	Success Factor
Communication across disciplines	Abandonment Misunderstandings	Constant KTT during project duration; define communication and boundaries
Involvement of multiple disciplines, backgrounds, and approaches	Misunderstandings	Turn into a benefit by learning from each other
Resistance to ideas	No collaboration possible	Build a network of experts willing to collaborate
Duration of development phase	Discouragement	Assess the market properly; ensure the product is scalable
Translation between fields	No marketspace	Find a market niche
Requirement of proof-of-concept	Discouragement	Determination of channels for production; pursuit of blue ocean strategy; find appropriate methods for validation
Duration of commercialization phase	Discouragement	Appropriate marketing, assess the market properly
Requirement to design new processes of production	Opportunity for patents; increase of time and costs	Procurement of sufficient funding; patenting
Requirement to build up new capacities	Increase of costs	Procurement of sufficient funding
Protection with patents	Legal protection for IP	Keep potential competitors out of the market; define IP of various partners
Long wait for return on investment	Discouragement	Procurement of sufficient funding
Clear research objective and specific goals, mandatory interdisciplinary thinking, open-mindedness, commitment, flexibility, environment for collaboration, willingness to learn from each other, reciprocal respect, endurance, deep understanding of biology, advising experts and impartial referees.[1]		

[1] Overarching topics and aspects that facilitate the BID process.

Table 3 summarizes the challenges of and the opportunities for BID projects, as reported by the developers of BID concepts and products. The topics address a) the collaboration and communication in interdisciplinary teams, b) the demands of the process, c) the production of viable prototypes, d) the time needed, e) the intellectual property (IP), and f) the costs. Each of these topics is linked to several research questions which must be addressed in further studies. For example, the role of team members is of interest, as current literature indicates [59,60]. Additionally, an assessment of problems that can be addressed with BID would be of help to fulfill the demands of the process, and strategies for patenting and funding would help to support future users.

As indicated by the business cases, and as sources of funding, especially when it comes to the establishment of a start-up based on a BID product, private savings/investments, governmental funding, and angel investments are possible ways of procuring sufficient funding.

BID developments can face specific challenges. In addition to the ones already discussed, such as longer phases for a proof-of-concept due to the complexity of truly understanding the biology and transferring it to engineering, technology and market validations are also challenging. As indicated before, this includes the preparing of a problem statement, which is an essential step at the very beginning of projects. The question of whether the problem identified is worth solving, especially with BID, must be answered early. In doing so, assessing the potential market at the very beginning is crucial, even though the assessment will be adapted once the development process progresses and the BID solution becomes clear. In addition, once academia and industry collaborate, further challenges arise which make knowledge transfer from research to application difficult. For example, the transdisciplinary work in BID asks practitioners from industry to understand the fundamental paradigm of BID, which encompasses the idea that an organism you may have never heard of holds the answer to your specific technological problem. On the other hand, one interview mentioned that they could not use research from the "ivory tower", but instead they needed to work with people with strong interdisciplinary capabilities. This raises the issue of teaching and training people involved in BID, which is a research topic on its own.

Another aspect that is part of the commercialization process is the marketing. Especially in BID, it is possible to develop a good marketing strategy, as nature has an inherently emotional aspect [8]. Therefore, once the product is valid, its value can be promoted effectively. However, marketing can be misused and in this context it is even more important to consider the definition of biomimetics in order to avoid weakening the concept [5].

4. Conclusions

With this article we aimed to increase the understanding of the overall BID process and to assist designers in overcoming challenges described as the "valley of death". We therefore addressed various topics regarding the implementation of BID concepts and their market entry. It is a first business case study based on the analysis of approximately 100 products, which gives insight into their development processes and the experiences of the developers. This will help future users of BID to better understand the process and characteristics of BID and to learn from derived success factors. By linking BID to the traditional innovation management process and to the "valley of death", we aimed to highlight that BID must be market-oriented and take into account the needs and expectations of industry. In combination with the success factors presented (Table 3), the challenges of the "valley of death" can be dealt with early in projects so that they may be anticipated.

Even though further research is necessary and will contribute to a deeper understanding of several aspects, we can make some recommendations for:

- implementing BID in product development,
- facilitating commercialization, and
- supporting existing and new industries (start-up community).

In this context, it is still necessary to analyze whether BID should be considered a unique way of problem solving or whether it will benefit from merging it with traditional development and innovation management processes. Research on that topic is ongoing.

As a result of our findings, we suggest that (a) a first assessment to identify which problems and projects can and cannot be addressed with BID should be performed. Research on that topic is ongoing and therefore is not presented here. In addition, (b) a customer and market analysis (product/market fit) and the identification of viable market segments are suggested, especially when it comes to early-stage startup ventures. We conclude that (c) a business and financial framework for commercialization is necessary, which includes critical questions about what the startup should do and not do in order to find a repeatable, scalable, and profitable business model. The framework makes these integrated choices to create a sustainable advantage within its market relative to rival startups and market incumbents. It additionally could help industries become more sustainable and competitive by adopting BID solutions that can radically transform an industry through the increased efficient use of natural resources, thereby mitigating environmental impacts. (d) The use of due diligence tools to better analyze and assess investments for BID is recommended. This means developing effective screening mechanisms to better identify, validate, and support early-stage biomimetic ventures. (e) Establishing business models/processes to accelerate the commercialization of BID solutions is recommended. These models could be based on the lean startup approach or regenerative design. The lean startup provides a scientific approach to creating and managing startups and getting a desired product to customers' hands more quickly. The lean startup model has as a premise that every startup is a grand experiment that attempts to answer a question. The question is not "Can this product be built?"; instead it should be "Should this product be built?". The regenerative approach uses the study of ecological systems to find solutions to human problems, to model patterns for industry, agriculture, and human habitats. They are in line with the BID approach to encourage the development of innovative solutions that address specific needs, pains, and/or desires of a particular target user or customer. Successful entrepreneurs have to understand their customer needs, especially how the customers experience a particular problem and why (and how much) it matters to them.

Lastly, BID can benefit from integrating with tools and methods from other disciplines, such as project and innovation management. As a benefit, those methods may already exist in the company or the team which allows BID to build upon existing expertise. Therefore, we assume that further research will focus on analyzing how existing tools and methods can be used and eventually be adapted for the BID process.

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