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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

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.

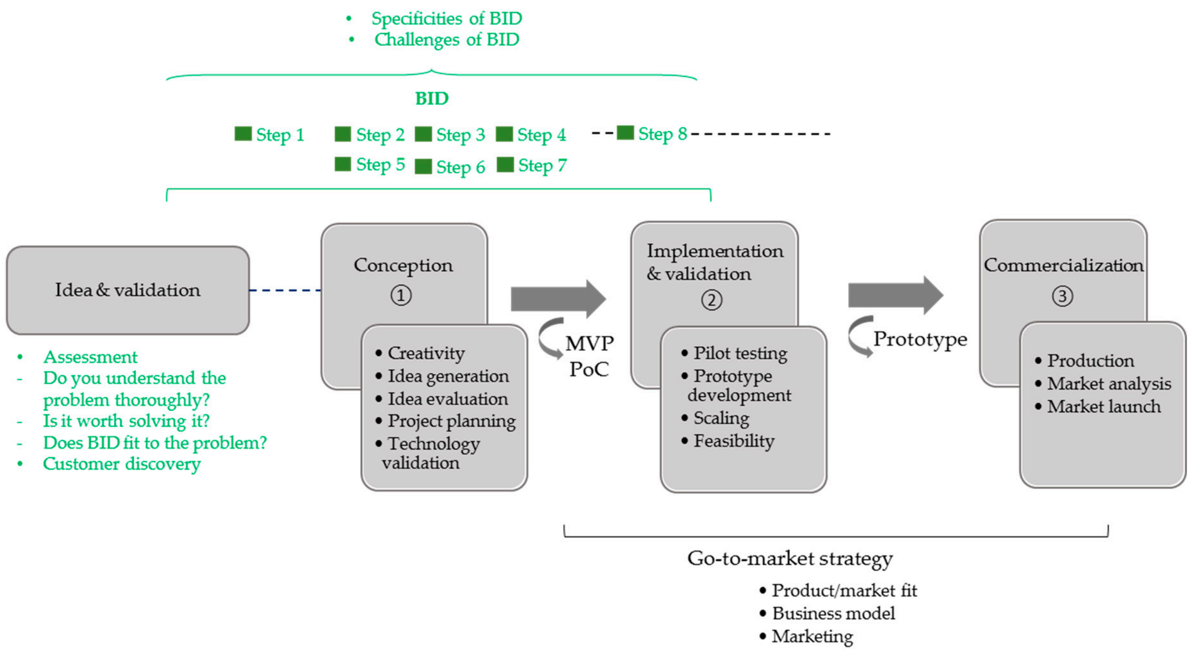

Figure 1. Phases of the innovation process linked to the eight steps of the biologically inspired design (BID) process as described with the unified problem-driven approach of biomimetics by Fayemi et al. [11]. ①, ②, and ③ indicate the main phases of a simplified innovation process. The eight steps of 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.

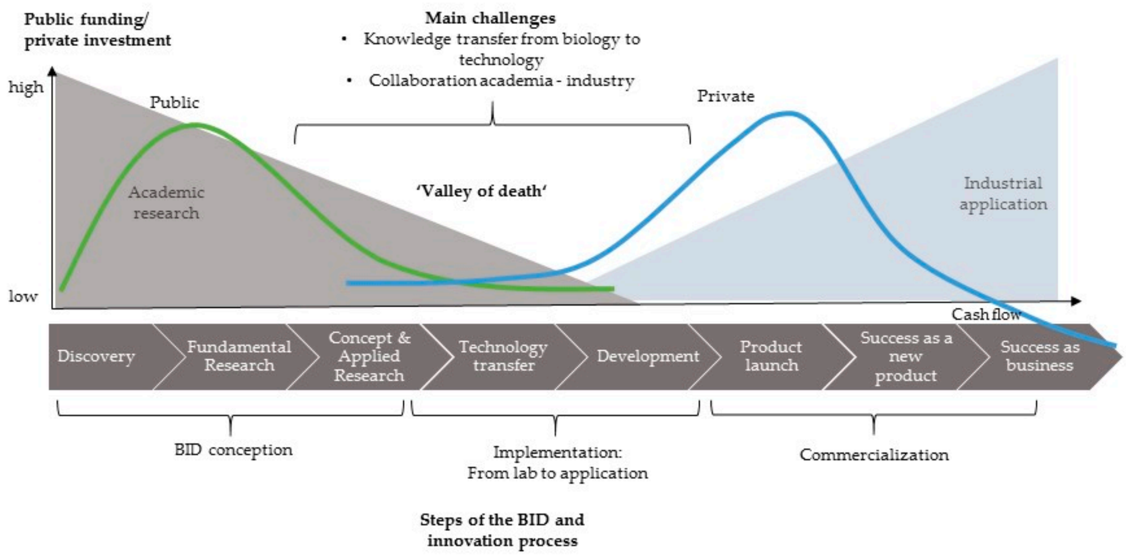

Figure 2. The "valley of death" in innovation and the context of the simplified BID process. Based on and adapted from [46,47]. BID: Biologically inspired design.

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.

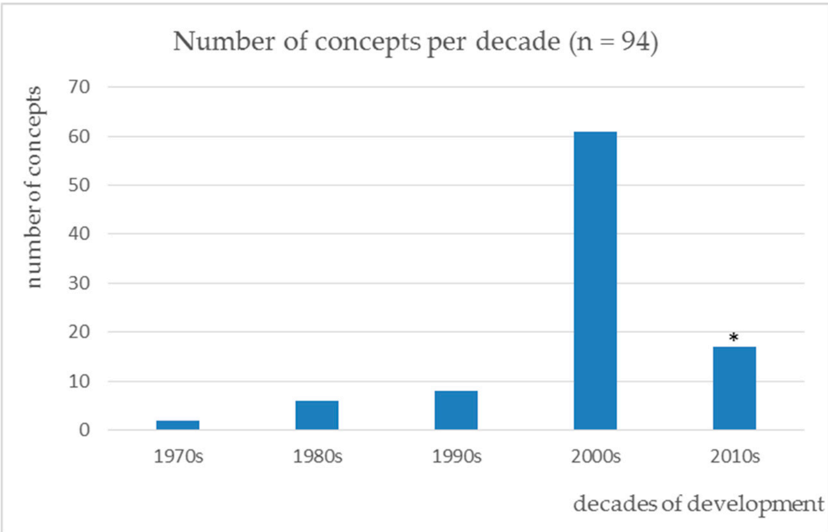

Figure 3. Number of BID concepts per decade from 1970 to 2012 (n = 94). *: The asterisk indicates that the underlying data cover only the first two years of the 2010s. Newly developed concepts and products in the years 2013–2019 must be added once they are researched.

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.

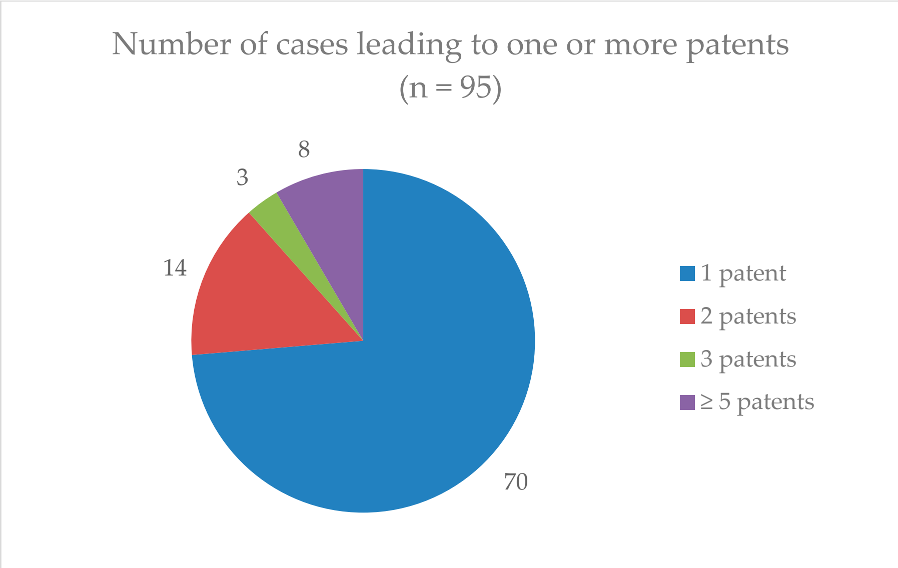

Figure 4. Number of patents per BID concept based on the BioM Innovation database [22]. As shown, 70 BID concepts led to a single patent (74%), 14 to two patents (15%), 3 to three patents (3%), and 8 to five or more patents (8%).

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.

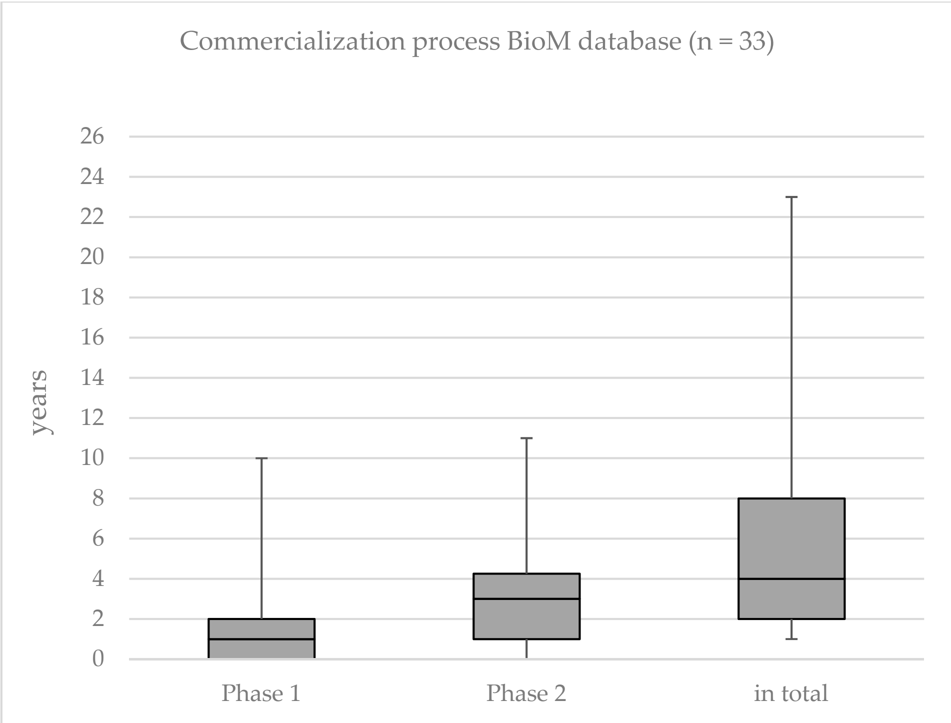

Figure 5. Duration of the commercialization of 33 BID products in years. Phase 1: concept to prototype; phase 2: prototype to market.

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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