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# Formulation and testing of a Biologically Inspired Design method tailored for industrial applications

**Application to the Separation Technology Sector**

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*A Krisztina, premurosa e paziente compagna di viaggio, musa e consigliera, che mi conduce fuori da acque perigliose, sortilegi ed antri di Polifemo.*

*Ai miei genitori, Rosalba e Mirco, che da sempre osservano con stupore e spesso malcelata ansia, le peripezie di questo Ulisse in cerca di una sua Itaca.*

*Sognata terraferma alla quale un giorno approderà; forse; chissà…*

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ABSTRACT
Over the last decade and a half increasing attention of the scientific community has been given to biologically-inspired design (BID), the process of selecting and emulating natural forms, processes and systems to generate innovative design. The potential for bio-inspired innovation is still largely untapped; BID methods and tools are not yet largely utilized especially within the industry, a sector with the potential for turning bio-inspired ideas into marketable innovation.
Starting from identifying factors which influence the utilization of BID by the business environment, this research aimed at answering the following broad research question:

*How should a BID method/Tool be designed and utilized in order to generate bio-inspired ideas more likely to become innovation in business environment?*

In order to answer the question, two main methodological approaches were followed:

- An exploration of natural evolutionary process and, by analogy, extraction of design principles to formulate innovation models more aligned with natural principles, where the ideation process is a continuous multi-stakeholders participative process;
- A review of literature on BID to identify key factors affecting BID effectiveness and based on these, extract possible solving strategies which led to the formulation of BID methods' Design Principles.

Based on the principles identified above, the following outputs were conceived:

- The *Evolutionary Innovation Model* (EIM) which is a conceptual Open Innovation/Coopetitive innovation model;
- The *Guild-based* (or *Sectoral*) *BID method* (GB-BID), which consists in a method to set up databases of biological solutions to be used to generate bio-inspired ideas of interest for industrial applications.

The GB-BID method, differently from already existing BID methods, is:

- <u>Sectoral:</u> conceived to be customized for specific industrial sectors;
- <u>Open:</u> conceived to promote Open Innovation/Coopetitive models;
- <u>Problem-based</u>: biological information are processed to be meaningful and useful for specific target groups (sectors) with specific problems;
- <u>Multi-level</u>: able to advice at different level of abstraction of the problem;
- <u>Inclusive</u>: biological information is stored in formats which can allow participation of non-technicians to the ideation process.

While the EIM remains, for the time being, a conceptual output, the GB-BID method underwent a process of testing and validation. In order to do this a GB-BIS Database has been conceived for the *Separation Technology sector*. It has been populated with relevant biological solutions responding to the main function "to separate". The database has been tested via a series of *Ideation Workshops* with different target groups (mixed background, engineering students and knowledge-based experts) and production of various *case studies.*

Despite some limitations of the research, mainly related to the limited amount of data generated by the ideation workshops, the following main conclusion can be drawn:

- In ideation workshops, the GB-BID method allowed generating bio-inspired ideas but in terms of ideation metrics it seems not significantly more effective than other BID methods tested (AskNature and SBF-DANE) in tight time bound ideation workshops. Further workshops of longer duration and different target groups will have to be conducted in order to revise/confirm the results.

- In case studies generation, the GB-BID method has been proven valid:
    - To extract broad (deep) design principles which can provide valuable indications to evaluate existing technology vis-à-vis natural principles and steer sectoral research toward innovative solutions.
    - To produce taxonomies of "robust" (with a certain frequency of occurrence in nature) biological solutions which could be utilized to evaluate existing technology vis-à-vis natural principles and/or to generate innovative bio-inspired ideas.
    - To produce novel design concepts for the specific sector which can become marketable innovation.
    - To produce bio-inspired ideas also for sectors not targeted by a GB-BID Database.

The results achieved so far by this research give indication that a BID method/tool with the attributes of the GB-BID method can indeed be beneficial to industrial practitioners for industrial applications. Attributes which are not explicitly present in other BID methods/tools. This however does not mean that other BID methods could not be tailored to embed these features and/or complement the GB-BID method. This aspect could be explored in further research activity.

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## LIST OF ABBREVIATIONS

BID - Biologically-Inspired Design ....................................................................................................... 16
DANE - Design Analogy to Nature Engine ........................................................................................ 103
EIM - Evolutionary Innovation Model ................................................................................................ 28
EU - European Union.......................................................................................................................... 33
GB-BID - Guild-based BID method ..................................................................................................... 28
HV - High Voltage ............................................................................................................................. 204
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SBF - Structure-Behaviour-Function ................................................................................................. 106

# MOTIVATION

## Personal Motivation

The personal motivation to embark in this investigation came from a series of considerations that I distilled following the last 24 years of worldwide experience as environmental engineer. In my career, so far, I dealt with formulation, implementation and evaluation of works, technical assistance and applied research projects related to several topics, linked to environment and sustainable development (water management, energy, waste, biodiversity protection, private sector development, climate change, education, agriculture). Projects implemented in both Developing Countries and Transition Economies Countries, working within organizations such as the European Commission, the United Nation Development Programme, NGOs, Consulting companies as well as Universities. Statistically speaking, during this rather eclectic path, I gathered a significant sample of case studies which allowed me formulating an opinion on how things around sustainability are progressing: not that good.
The worsening trend of global environmental, social and economic indicators stand me right.
From my personal experience (which I nevertheless enrich hereby with references) the main reasons, all interconnected, which contribute to this situation are the following:

1. *Fragmented culture* and segregated knowledge with consequent difficulties in dialoguing among different disciplines and therefore lack of effective multi-transdisciplinary approaches to find solutions to complex problems (Capra 2002) (Capra and Luisi 2014)
2. *Lack of Systemic view* of the World as well as lack of System Thinking skills, again leading to incapacity of addressing and solving complex problems (Capra 2002) (Meadows 2009). A consequence of this it is neglecting to properly understand the context within which we want to operate; introducing processes and technologies *now* without considering what will happen *tomorrow*. Countless projects in Developing Countries funded by International Donors I experienced miserably failed because of lack of understanding of local contexts.
3. *Lack of connection and communication* among relevant stakeholders which should be involved in solving complex problems. Someone necessary is always missing at the decision-making table (Waltner-Toews, Kay, and Lister 2008).
4. *Trust in the blue-print approach*. Models which are developed and suitable for a certain Economy may not be suitable and even be detrimental if introduced in another one (Schumacher 1973) (Yunus 2008). Again, I refer to failures of Development and Cooperation projects aiming at introducing technologies and development models mature for the Western World but not suitable for Developing Countries; expecting too ambitious leaps forward within a short time.
5. *Preferring solutions which maximize* the benefits of few rather than *optimize* the benefits of many. This is not a rather "ethical" reason but unfortunately it is probably the main responsible for hampering sustainable development (it is also known as *the tragedy of the common*)
6. *Thinking incrementally rather than radically*. To avoid destabilizing the dynamic equilibrium of economic/social systems fearing to send them into chaotic state, we avoid considering and exploring completely different trajectories of development. We hardly evaluate the trajectories of technological evolution to remember why a certain technology was developed becoming successful on the market but highly detrimental for the environment. Already well-rooted technology and processes could be re-thought from scratch; not improved incrementally, but completely re-designed and in case replaced with more radical and sustainable innovation.

In short: *we tend to fear radical changes preferring maintaining the status quo with a guaranteed maximisation of returns and we rush things without having them assessed under different perspectives and discussed with the right people.*

Then, coming across the concepts of *Bio-inspiration* and *Biomimicry*, I came to realize that Nature is not affected by many of the lacks above.
Not because Nature is necessarily "cleverer" in designing, but because it had much more time to experience complex problems and try countless solutions. Some of them could not adapt to changing conditions and are now fossils, some are well-adapted and resilient and survived on the planet for millions of years, some others may be in a trajectory of extinction because unsuitable to future conditions.
At a higher level Nature operates in form of (eco)systems where all the elements are highly interconnected in nested networks and where communication and feedback loops are key for development and evolution.
Nature seems not interested in maximizing but rather in optimizing. A champion of compromises. Rather than aiming for "win-win-win-win…solutions", where in our society "to win" means to be n.1, Nature rather seeks for "*ok-ok-ok-ok…solutions*" where nobody gets to be n.1 but everybody get a satisfactory position; and in doing this, the number of "Oks" for each natural solution seems much higher than our number of "Wins".
Nature does not use the blue print approach but it adapts solutions to the context where they are applied, using locally available resources. In fact, in long terms, Nature not only adapts to pre-existing contexts but also modifies the context to better adapt (a concept known as *niche construction*). This latter we also do, but Nature does it creating anyway conditions conducive to more life, which, in our case, it is far from the truth.
Nature seems evolving mainly incrementally under the scrutiny of natural selection but does not avoid radical changes when conditions arise[1].

That is why as a professional but also as a person, since the last ten years, I tried to respond to these highlighted issues progressively complementing my knowledge and skills in the following way:

- I trained in Education for Sustainability (Certificate in Education for Sustainability at the Schumacher College in UK) to learn tools to engage people in transformative learning process around sustainability issues as well as effective multi-stakeholders dialogue.
- I trained in Biomimicry and Biologically-Inspired Design approaches (BID) (Master in Biomimicry at the Arizona State University and Certification of Biomimicry Professional at the Biomimicry3.8) to better understand Living Systems and how to learn from them to frame and tackle complex problems and improve technologies and processes.
- I co-founded the only Italian start-up so far fully dedicated to bio-inspired design. Since 2013 Planet s.a.s (planet.wemimic.it) has been my "case study" for testing Biomimicry in the field, developing our own bio-inspired products and assisting companies in innovating their products with a bio-inspired approach.
- I co-founded Biomimicry Italia (biomimicryit.org) as network to disseminate Biomimicry in Italy holding several public and private sector workshops to promote and teach BID in Italy and abroad.

This research, from a personal perspective, represents another piece of the puzzle in my professional development as a provider of potentially more sustainable solutions to complex problems.

## Scientific Motivation

The scientific motivation of this research derives from knowledge gathered during my direct professional experience as well as knowledge from scientific literature (as it will be described in Chapter 1 and 2) which pinpoints at the existence of issues which prevent Biologically-Inspired Design larger diffusion and success:

[1] All the above considerations about Nature will be further substantiated in chapter 4 and they have been mentioned here with the purpose of introducing my motivation to this research.

- The business sector, one of the main actors which could turn ideas into innovations, has not yet systematically introduced BID in its ideas generation process;
- The business sector is rather prudent in investing and using BID to innovate product due to uncertainty in estimating its cost/benefit ration (for instance the firm Biomimicry3.8, specialized in BID, works mainly with highly profitable Fortune 500 companies);
- The vast majority of BID methods have been developed by engineers/designers within Academia environment where bio-inspired *ideas* may be conceived, prototyped and even patented but they hardly succeed in reaching the stage of *innovation* on the market because of lack of technology transfer to the business sector;
- Existing BID methods developed in Academia serve all sort of problems. No assessment on their applicability in specific contexts (sectors) has been carried out, neither attempt of developing tailor-made methods for specific business sectors.

This research wants to start addressing the above issues proposing solutions which can bring BID closer to the business sector.

# PART 1

# INQUIRY AND RESEARCH METHODOLOGY

# 1. INTRODUCTION: Bio-inspiration and Innovation

This research aims at exploring and bridging some gaps between BID and its successful use by the business sector in its effort to innovate. Therefore, two macro-domains of knowledge are considered:

- the domain of **Biologically Inspired Design methods and tools**
- the domain of **Innovation Management**

It is therefore relevant to provide an initial short introduction to both of them highlighting relevant terms and concepts when in the next Chapter 2 a deeper analysis of their state of the art is provided which is instrumental to identify the research question.

## 1.1 Criteria for selection of references

Before introducing the topic of the research, an initial description of the criteria followed to search and select references is provided. This research was informed by the PRISMA statement, consisting of a generic four-phase flow diagram and checklist providing formal guidance on conducting and reporting systematic reviews (Moher et al. 2009). In particular for each of the phases:

**Identification:** The topics considered in this research are numerous and for each one of them the identification of sources of information generally followed a *cascade* approach, starting from books on the topics whose reference lists refer to articles whose reference lists refer to other articles. Additionally, keywords have been utilized to retrieve relevant articles from Google Scholar. All information derived from sources in English language but one (Pizzocaro 2015 in Italian). Overall more than 850 documents where gathered of which 260 on biological systems utilized for the testing and validation process.

**Screening:** the contents of articles were screened in order to assess their relevance for the research. Often reading abstract was not enough to judge the relevance of the article and full reading has been carried out.

**Eligibility and Included:** All the papers utilized and referenced in this work have been either published on scientific peer-reviewed journals, included in conferences' proceedings or published internally to Universities. Books consulted have been published by scientific publishers. When information came from a not-confirmed peer-reviewed paper or book, a double check has been carried out to find other research groups and possibly peer-reviewed papers referring to similar information or results, therefore going back to the "identification" phase (sometimes multiple references are indeed quoted in this research).
For each topic treated, the researcher did not focus on a single research group's work but expanded the research until he considered having reached a solid confirmation of the information reported. The relevant documents retained are the ones listed in the bibliographies of the main body of this thesis and its annexes.

## 1.2 Bio-inspiration and BID methods and tools

Tracing the origins of bio-inspiration, the use of nature as source of inspiration to solve problems, is hard. Ancient human artefacts, anthropological and cultural studies as well as studies of evolution of technology abound of evidence that humans have consistently taken inspiration from the natural world, its physical phenomena and surrounding living systems (Pizzocaro 2015; Vincent et al. 2006). Inspiration has been taken from a visceral perception and understanding of natural phenomena based on the five senses to planned and structured observations.

Another aspect of bio-inspiration difficult to assess is the cognitive process linked to the retrieval and use of the biological analogy. If nowadays bio-inspiration is studied and utilized as a conscious and structured approach to solve problems, it cannot be excluded that many of the technological solutions conceived by human kind since its dawn could have been triggered by an unconscious reference to biological solutions (being the outside natural world the only "learning space" for humans).
When considering bio-inspiration as a conscious act, Leonardo da Vinci is most probably the most known of the earlier bio-inspired designers (though evidence of conscious bio-inspiration to emulate silk worm can be traces back to 3000 years (Vincent et al. 2006)). Known for his frequent encounters with the natural world in solitude (Capra and Luisi 2014), he was able to generate design concepts inspired by nature and prototype them, within the limits imposed by its time in terms of biological knowledge, research tools, production processes and materials.
These barriers are nowadays been largely removed thanks to advanced tools for exploring and understanding biological processes at the scale of nano-metres, as well as production technology and materials to reproduce nature's solutions (Bar-Cohen, 2006; Bhushan, 2009).
Using analogies from the natural world does not only provide possible solutions to a (functional) problem but, from a cognitive process perspective it helps removing design blockages (fixations), increase divergent thinking and "thinking outside the box" (Moreno et al. 2015; Christensen and Schunn 2007; Chiu and Shu 2007). Therefore this renewed interest in the conscious use of Nature as a model has contributed to the development of structured approaches and tools to assist problem solvers of all kind (not only designers, engineers, architects but also planners, economists, cognitive and social scientists) in their endeavour of utilizing natural analogies to generate solutions (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006).
With this progressive development of bio-inspiration as a discipline, the process of transferring knowledge from the domain of biology to solve problems of other domains has been attributed different terms such as *Bio-inspiration*, B*ionics, Biomimetics, Biomimicry*, *Biologically-Inspired Design* and *Bio-inspired Design*. Tracing the origins of some of these terms is difficult and authors who attempted it are also prudent in determining names, date and definitions (Gleich et al. 2010). These terms are sometimes used synonymously, sometimes promoted as decoupled and applicable for different specific purposes.
If it is not the objective of this research to provide further insight on this debate, it is however important to frame the terminology in a way to make sense for this research.
The distinction and relation among the terms adopted in this research is based on other authors proposals (Shu et al. 2011; Fayemi et al. 2017; Helfman Cohen and Reich 2016; ISO 2015; Tan et al. 2019) and adjusted on the specific experience of the researcher as presented in the graph of Figure 1-1. The graph considers *Bio-inspiration* as overarching term where a biological system is utilized *consciously* or *unconsciously* as analogy to stimulate the creative process to solve any sort of problem (technical, social, economic, philosophical). Unconsciously meaning *un-aware*, without any premeditated plan of exploring the domain of biology nevertheless having a biological analogy appearing in *a-ha* moments; maybe thanks to pre-existing biological knowledge of the problem solver. *Bio-inspiration* is not necessarily a heuristic and definitively not structured with an ontology because the biological analogy can be received and interpreted by the receiver through different media. It can stimulate, not necessarily the solution of a specific problem, but simply suggest new areas of research in non-biological sciences and technology (Whitesides 2015).
Bio-inspiration embeds Biomimicry. *Biomimicry*, as defined by Janine Benyus (Benyus 1998) is the *conscious* process of emulating nature in terms of *form*, *processes* and *ecosystem*. Therefore, at this level the unconscious use of biological analogies is removed to give space to conscious one only. The term Biomimicry does not imply any specific method or tool in itself (the term was coined by Benyus in her book *Biomimicry* which is a collection of case studies of bio-inspired projects) at this stage and it does not refer to any specific problem's domain but all of them. Biomimicry can be applied for innovating products, technology but also communities, economy and politics. Furthermore biological systems are not only consulted to find new solutions (nature as *method*) but also to *evaluate* existing

solutions (nature as *measure*) as well as defining ethics (nature as *mentor*) (Baumeister and et Al. 2011).
When exploring literature using terms like *Biomimetics* and *Bionics* the problem's domains addressed is more related to the design of technology (robotics, materials, structures, information systems, etc.) (Gleich et al. 2010) (Speck et al. 2017) rather than other non-technology-oriented domains (such as sociology, economy, management, etc.). Furthermore educational courses about biomimetics and bionics are usually embedded in educational curricula of Engineering, Design, Architecture or related technical disciplines (Gleich et al. 2010). This is the reason why, in Figure 1-1, they have been positioned as embedded within Biomimicry.
The term *Biologically-Inspired Design* (BID) usually identifies a series of structured methods and tools belonging to the broader category of *Design-by-Analogy* approaches which fall within the even broader subject of *Ideation Processes* (Moreno et al. 2015). Their aim is to assist the problem solvers by stimulating the ideation process proposing useful biological analogies described in through different models and detail of information.
BID has been therefore located within Biomimicry but overlapping Biomimetics and Bionics as BID methods and tools are utilized in Biomimicry and Biomimetics/Bionics processes.

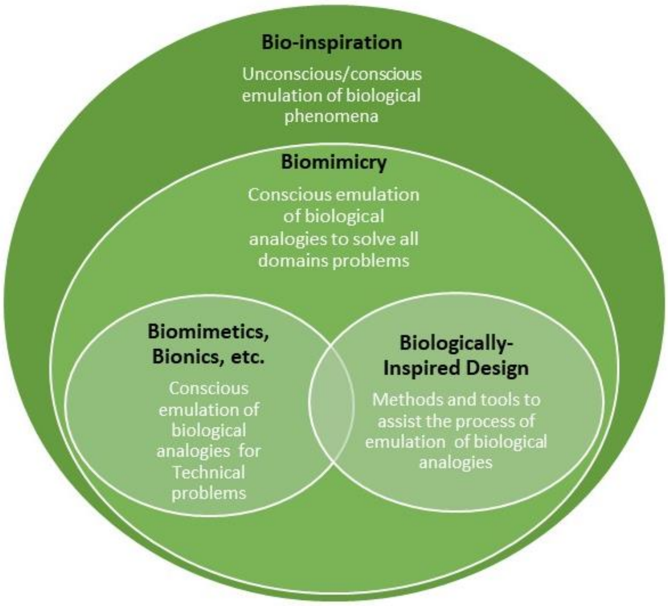



*Figure 1-1:* A proposal for an understanding and connection among processes and tools using biological models as analogy.

## 1.3 Innovation process and its management

The term *innovation* is subject to countless classifications, typologies and categorisations in professional literature. Starting from the Schumpeterian definition (Ruttan 1959; Śledzik 2013), 60 different definitions of innovation have been collected by (Baregheh, Rowley, and Sambrook 2009) from the various disciplinary literatures in topics such as Business and Management, Economics, Organization studies, Innovation and entrepreneurship, Science and Engineering, Knowledge management and Marketing. These definitions have been categorized according to specific attributes, which ultimately allowed the authors to distil and propose a multi-disciplinary definition of Innovation. The authors comment that if it could be argued that each discipline requires its own discipline-specific definition, as business and research become more inter- and multi-disciplinary, there is the need for a more integrative definition to enable the development of common meaning and shared understanding of the various dimensions of innovation. Therefore, they suggested a definition that is hereby integrated (in *(…)* )from the one proposed by (OECD 2002):

**Innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service, processes, *(and marketing, organisational and business methods)* in order to advance, compete and differentiate themselves successfully in their marketplace.**

This definition is therefore the one that this research takes as reference as he considers it the most suitable to be combined with the domain of Biomimicry and BID.
By definition, all innovations must contain a degree of *novelty* (OECD 2002; Carlile and Lakhani 2011). Novelty is understood in Schumpeterian terms as the appearance of something that is intrinsically new, i.e., something that is not contained within data and that is not a logical consequence of the unfolding of a previously existing state (Encinar and Muñoz 2006). It can also represents originality, and as such, it distinguishes between the creation of new knowledge and the adoption and use of existing one (Knell and Srholec 2009). While innovation does require novelty, not much has been explored on the fact that not all sources of novelty may lead to innovation (Carlile and Lakhani 2011). Three concepts for the novelty of innovations are highlighted by OECD (OECD 2002):

- *new to the firm* (a product, process, marketing method or organisational method may already have been implemented by other firms, but if it is new to the firm),
- *new to the market* (the firm is the first to introduce the innovation on its market), and
- *new to the world* (when the firm is the first to introduce the innovation for all markets and industries). (OECD 2002).

The process of innovation can be divided into stages, from the moment of the initial decision to tackle a problem, to the final commercialization of an innovative product solving that problem. Different authors provide different ways to split the process in stages and sub-stages (Tidd J. , Bessant J. 2014). Conscious of the debate and different interpretations, in this research it has been decided to consider the following categorization:

1. **Ideation**: the stage where problems are analysed and framed and ideas for solutions are formulated and screened leading to design concepts. Irrespective of the type of innovation, the starting point is an idea with a new insight of a single individual. To turn this idea into an innovation, it has to be made explicit so that the knowledge can be shared with other members of the organization and implemented. (Björk and Magnusson 2009) (Trott, P. 2008; Varjonen, V. 2006)
2. **R&D:** the stage includes Research activity, Proof of Concept, Prototyping and eventually IP protection of the invention generated from the initial ideas. To be noticed that in this statement a clear distinction is made between *ideas* vs *invention*, the latter being the physical embodiment of the former and invention vs innovation where the latter is not synonymous neither bound by the former ((Ondrej Zizlavsky 2014) referring to (Tabas, J. 2010))(Tidd J. , Bessant J. 2014)
3. **Product Development**: the stage regarding the embodiment of the selected concepts and prototypes into a physical product that can be reproduced for commercialization.
4. **Commercialization**: testing, launching and marketing the new product. The innovative product does not necessarily have to be commercialized but in some cases (for instance for Organisational and Business innovation) it could be just embedded in the same entity which developed it.

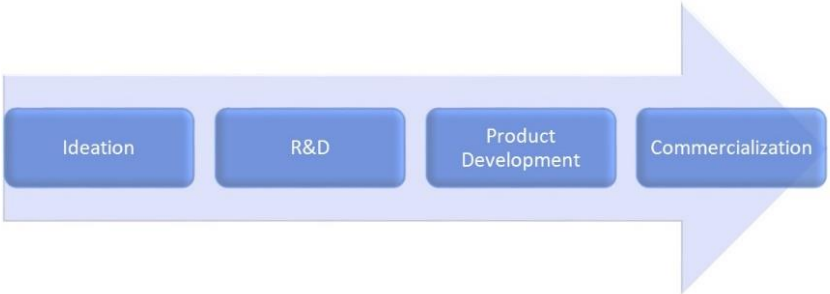



*Figure 1-2: Four phases of the process of innovation. From Ideation to Commercialization of the product.*

Despite the apparent linearity of the process (see Figure 1-2), it is not excluded that some reiterations among phases 1 and 2 may be necessary before proceeding to phase 3 and 4.
The term *Innovation Management* is also open to debate. However, it can be broadly defined as *the systematic promotion of innovations in organizations to generate benefits* (Adams, Bessant, and Phelps 2006) and includes tasks of planning, organization, management and control. It can be split under two major pillars:

- Organizational development activities: so that ideas are always created in the organization and implemented into successful innovations.
- The actual innovation: the active search, development and implementation of ideas. This requires, for example, creativity and project management.

Based on a review of models of innovation management Adams et al. (Adams, Bessant, and Phelps 2006) propose a synthesized seven-factors framework of innovation management process: inputs management, knowledge management, innovation strategy, organizational culture and structure, portfolio management, project management and commercialization. This framework allows them to identify areas of measurement (variables/indicators) for each one of the seven factors (Figure 1-3). This in the effort to quantify, evaluate and benchmark innovation competence and practice to eventually improve the competitive success of innovative companies.

| Framework category | Measurement areas |
|---|---|
| Inputs | People<br>Physical and financial resources<br>Tools |
| Knowledge management | Idea generation<br>Knowledge repository<br>Information flows |
| Innovation strategy | Strategic orientation<br>Strategic leadership |
| Organization and culture | Culture<br>Structure |
| Portfolio management | Risk/return balance<br>Optimization tool use |
| Project management | Project efficiency<br>Tools<br>Communications<br>Collaboration |
| Commercialization | Market research<br>Market testing<br>Marketing and sales |

*Figure 1-3: Seven-factors Framework of Innovation management from (Adams, Bessant, and Phelps 2006).*

It is important to frame the concepts of innovation and its management because (as it will become more evident throughout the research) not only bio-inspiration holds the promise of generating innovative products to be put successfully on the market, but it can also support the innovation of the innovation process itself. Organisational and physical structures of firms as well as entire innovation systems could be reviewed and innovated in the light of natural principles (especially within the scopes of Circular Economy) (Mead 2014); however this research rather focuses on product innovation.

## 1.4 From bio-inspired research to Innovation

The two domains introduced above (Bio-inspiration and Innovation) currently find their main connection in the *ideation phase* of the product innovation process.
BID methods can be utilized by different actors in the problem solving activity to generate ideas which could eventually proceed through other phases of the innovation process such as R&D and Product Development. It is therefore important to investigate up to which extent Bio-inspiration is contributing to improve the management of the innovation and as a consequence the competitiveness of companies.
The general concept of looking at nature for solutions is by now broadly known and widespread (from Google search in Jan. 2020 of terms such as Bio-inspiration - 196M, Biomimicry - 3.1M, Bionics - 64M, Biomimetics - 8.2M, BID - 7.8M); however, the success of bio-inspired products is not. Few and disperse studies and statistics are available on the diffusion of biomimicry at different stages of the innovation process. Below, an account and analysis of what is available to the best knowledge of the researcher.
For instance, the Fermanian Institute produces the *Leonardo da Vinci Index* to measure activity in the field of bio-inspiration. Figure 1-4 below highlights the progression of the index in the last 15 years (Fermanian Business & Economic Institute 2013). In 2010, the Institute also provided an estimate of the impact on the market that industries could have by 2025 by deploying new materials, products, designs, processes and systems based on emulating the natural environment (Figure 1-5).

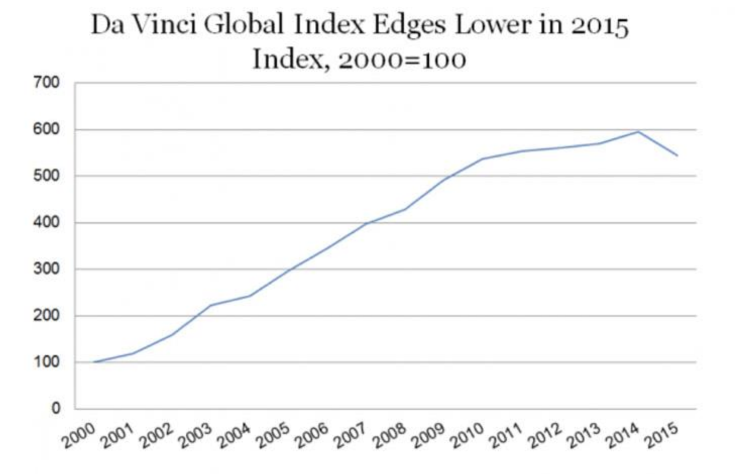



*Figure 1-4 : The Da Vinci Global Index.*

It combines, weighting them, the following indicators:
Number of Scholarly Articles (worldwide - Source: Thomson Reuters Web of Knowledge Database)—30%, Number of Patents (in USA) —30%, Number of Grants (in USA) —15%, Dollar Value of Grants—25%. The various data sources were searched with the following key words—Biomimicry, Biomimetic, Biomimic, Biomimics, Bio-inspired; these were chosen because most commonly used terms to refer to the field in the United States.

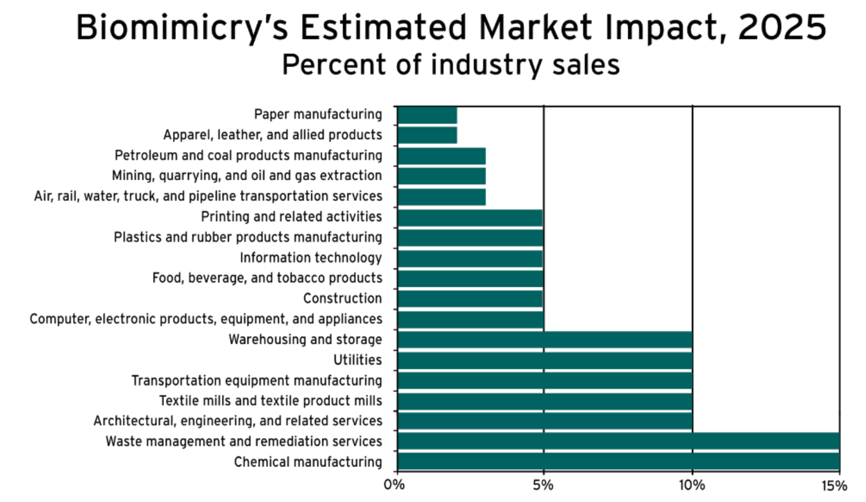



*Figure 1-5: Biomimicry's estimates of the total market shares for various industry groups, defined in terms of sales, that could be impacted by 2025 (Fermanian Institute 2010).*

If the Da Vinci index clearly shows the increase in the interest of biomimicry, both in research and patents filing over the last five years, it is rather an indication of *the potential* of biomimicry to provide businesses with more efficient and sustainable solutions, but it does not reflect the penetration in the market of bio-inspired products.

The growing interest in bio-inspiration within the scientific community is also reported by T. Lenau (Torben A. Lenau, Metze, and Hesselberg 2018) (Figure 1-6) as well as by Lepora (Lepora, Verschure, and Prescott 2013) who identified five distinct themes of research such as robotics and control, ethology-based robotics, biomimetic actuators, biomaterials science and structural bioengineering (Lepora et al 2013).

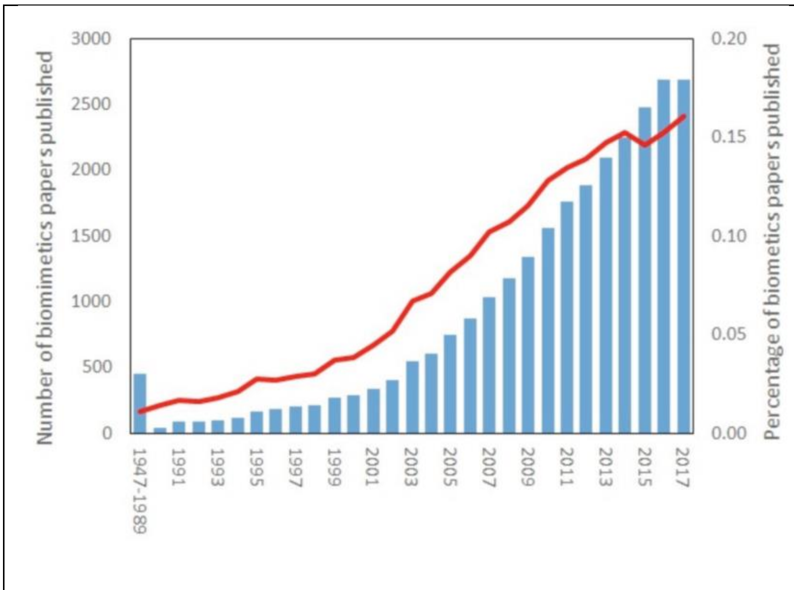



*Figure 1-6 The number of published biomimetics papers in ISI Web of Science.*

The search was done on articles in the Web of Science core database using the search terms 'biomim*', 'bionic*' and 'biologically inspired' (TS = (biomim* OR bionic* OR biologically inspired)) in the title, keywords or abstract. To get proportional data the number of hits was divided by the total number of published papers (which were assumed to be found searching for 'a'or 'the' in the title, keywords or abstracts – TS = (a OR the*). The bars indicate the number of published biomimetics papers, while the line indicates the proportion of these papers out of the total of all published papers. From (Torben A. Lenau, Metze, and Hesselberg 2018)

The BioM Innovation Database produced the first worldwide analysis of products deriving from a BID process (Jacobs, Nichol, and Helms 2014). At the time of the publication, the BioM Innovation Database contained 380 cases initially identified through search in popular literature, and since then it seems it has not been updated (see also more recently analysis from (Chirazi et al. 2019)). The database distinguishes product's entries according to *concept*, *in development*, *commercially available* and *discontinued*. A concept is defined as one that doesn't have yet a proven prototype developed, but the sound theory supports the probability of functionality; a product in development is one in which there is proof of concept; a commercially available product is one readily available to an average consumer; and a discontinued product was once commercially available but is no longer.

Of the 380 cases, the product phase of 379 was identified; 116 identified as being commercially available to the general consumer, 220 in development (mostly with prototypes) with limited availability, 29 still unpatented concepts (or patent-pending), and eight were discontinued after having been commercially available (Jacobs, Nichol, and Helms 2014).
Regarding the distribution around the world of the different products and their phase of development, Figure 1-7: *Distribution of biomimetic product phase* gives an account:

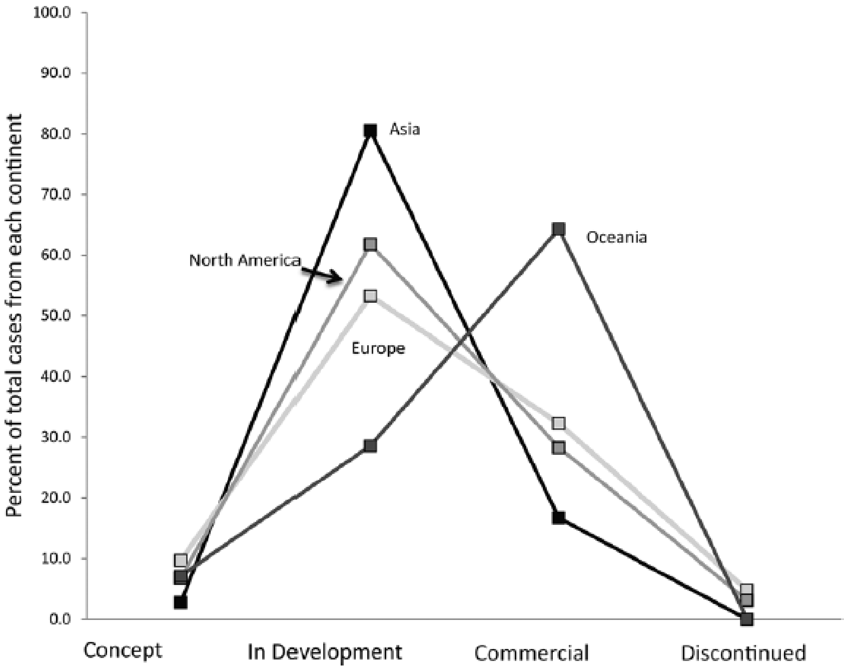



*Figure 1-7:* Distribution of biomimetic product phase from by continent from (Jacobs, Nichol, and Helms 2014).

To be also highlighted that the biological transfer to the product concerns around 35% with form, 17% with processes, 1% with interaction; the remaining emulate a combinations of the three.

A recent study of the application of Biomimicry in the Nordic countries (Lenau, Orrù, and Linkola 2019) highlights that over 100 organisations and almost 100 professionals from the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) are engaged in biomimicry/biomimetics/bio-inspiration related activities. The findings are categorized into four categories: academic research and development/ industry/ education and training/ forums and innovation platforms.
Almost half of the activities (53%) were categorized as academic research and development; one-third (31%) fell into category industry which includes a wide range of companies from design and architecture to business consultancy. Other two categories of actors were education and training, and forums and innovation platforms accounting each for 8% of the activities.
Within the Industry segment (46 companies), the sectors with the higher percentage of biomimicry activity are consulting companies (20%), urban planning and architecture (17%), material development (14%), product development (12%) and water and sanitation (12%).
The study also provides a presentation of the other European countries with approximately over 40 significant actors with four countries leading: Germany, UK, Switzerland, and France.
In this respect, the study is considered approximate as many European actors working with biomimicry and biomimetics of which the researcher is aware of (both in Academic or Industry) have not been mentioned.

## 1.5 Working packages of this research

The researcher considers important to highlight, already at this point, that the research will be divided into two main working packages related to two Research Sub-Questions derived from a main Research Question; packages which will run in parallel. One of this will generate conceptual outputs and the other operative outputs which will be subject to testing and validation procedures (see Figure 1-8). In particular:

1 *Formulation of Conceptual outputs*. The researcher considered valuable to carry out a review of several topics related to Innovation processes and BID. The information gathered have been framed in a more organic/systemic way and allowed the formulation of conceptual outputs that, despite not undergoing a testing and validation process, are considered valuable because they can provide inspiration for identifying further research questions when combining BID and Innovation processes. Because these conceptual outputs are not subject to testing and validation, the knowledge upon which they have been developed, has been largely confined into the *Analysis of the Context* which is included in Annex 1. However most relevant parts are reported in the main body of the thesis - Chapter 2/State-of-the-art - so as to allow the reader to follow the entirety of the research without necessarily consult Annex 1.
2. *Formulation of Operative outputs*. From the analysis of the context, specific issues are selected which will be part of the state-of-the-art upon which the researcher will build up his operative activities producing new knowledge. These issues are described in Chapter 2.

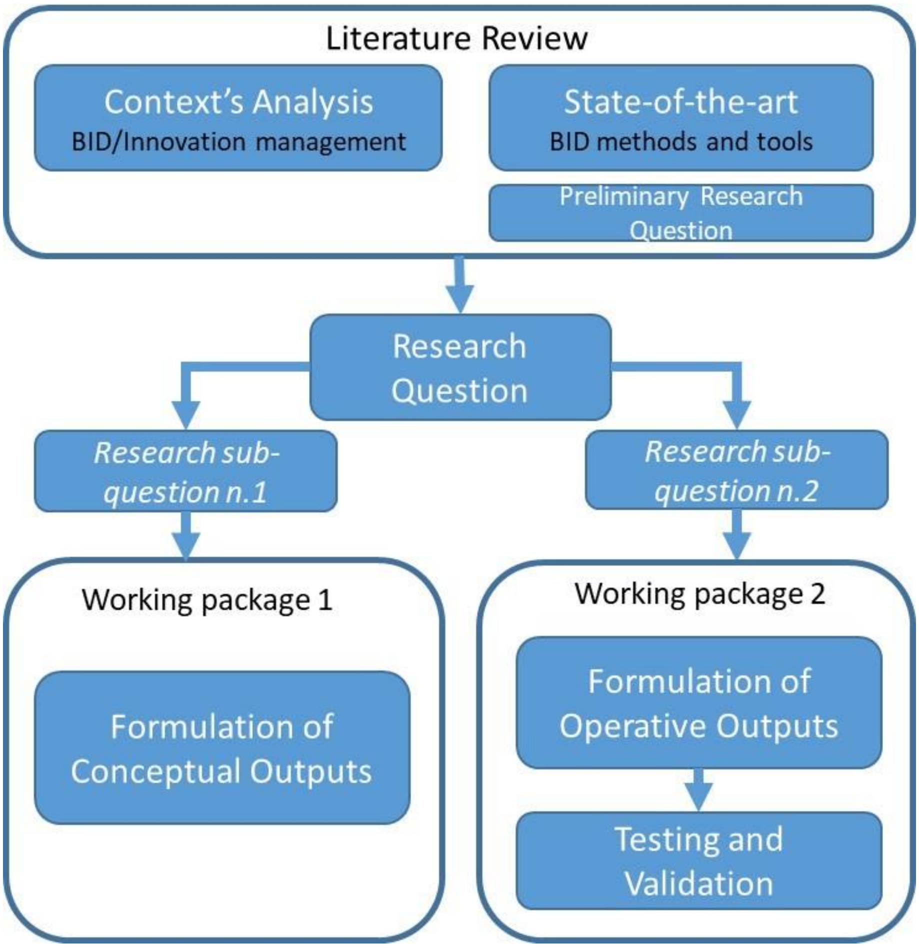



*Figure 1-8: General structure of the research from the Context's Analysis/State of the Art (which includes a preliminary research question) to the Research Question and the split into working packages for each sub-question concerning Conceptual and Operative outputs.*

## 1.6 Thesis Structure

The research undertaken is divided according to different phases reported in different parts and chapters. Figure 1-9 provides an overview.

*Part 1: Inquiry and Research Methodology*, it includes this initial introductory Chapter, Chapters 2 and 3.

- Chapter 2 provides relevant elements of the context analysis on Innovation processes (largely included in Annex 1) and the state of the art on BID methods upon which the research is built on. The Chapter is developed in order to provide a qualitative answer to a Preliminary Research Question: "*Which are the key factors to be considered when developing a BID method to make it usable by the business sector?*". Based on literature review, the answer is presented through a series of tables listing key factors and related considerations. The Chapter closes with the formulation of the Research Question and two sub-questions.
- Chapter 3, on the basis of the Research Question and two research sub-questions, provides a description of the methodological approach followed in the research.

*Part 2: Investigation and Proposals*, it includes Chapters 4 and 5.

- In Chapter 4, following the research methodology proposed, a search into biology is carried out to explore the processes of novelties generation and innovation from the point of view of nature (exploring the principles of natural evolution). This allows identifying biological strategies and extracting related design principles useful to compare current best practices of innovation management with biological strategies.
- In Chapter 5, considering the principles extracted in chapter 4 and some strategies derived from the key factors identified in chapter 2, two tools are formulated: the *Evolutionary Innovation Model* (EIM) and the *Guild-based BID method* (GB-BID). The former is a conceptual outputs, the latter is an operative output which is subject to the testing and validation procedure.

*Part 3: Testing and Validation*, it includes Chapters 6, 7, 8 and 9.

- In Chapter 6 the testing phase of the GB-BID method begun with the selection of the domain for testing, the Separation Technology sector, and the adaptation of the GB-BID method to that sector preparing the GB-BID Database on Separation;
- In Chapter 7 the description of the tests carried out through ideation workshops with different target groups and comparing different formats for biological information considered by different BID methods. The effectiveness of the formats tested are measured in terms of ideation metrics;
- In Chapter 8 various case studies generated from the GB-BID Database are described in detail;
- In Chapter 9, based on the results of the testing phase, conclusions are drawn on what has been achieved through the research as well as proposed follow-up activities. It also highlights both major original contributes and innovative research methodology utilized.

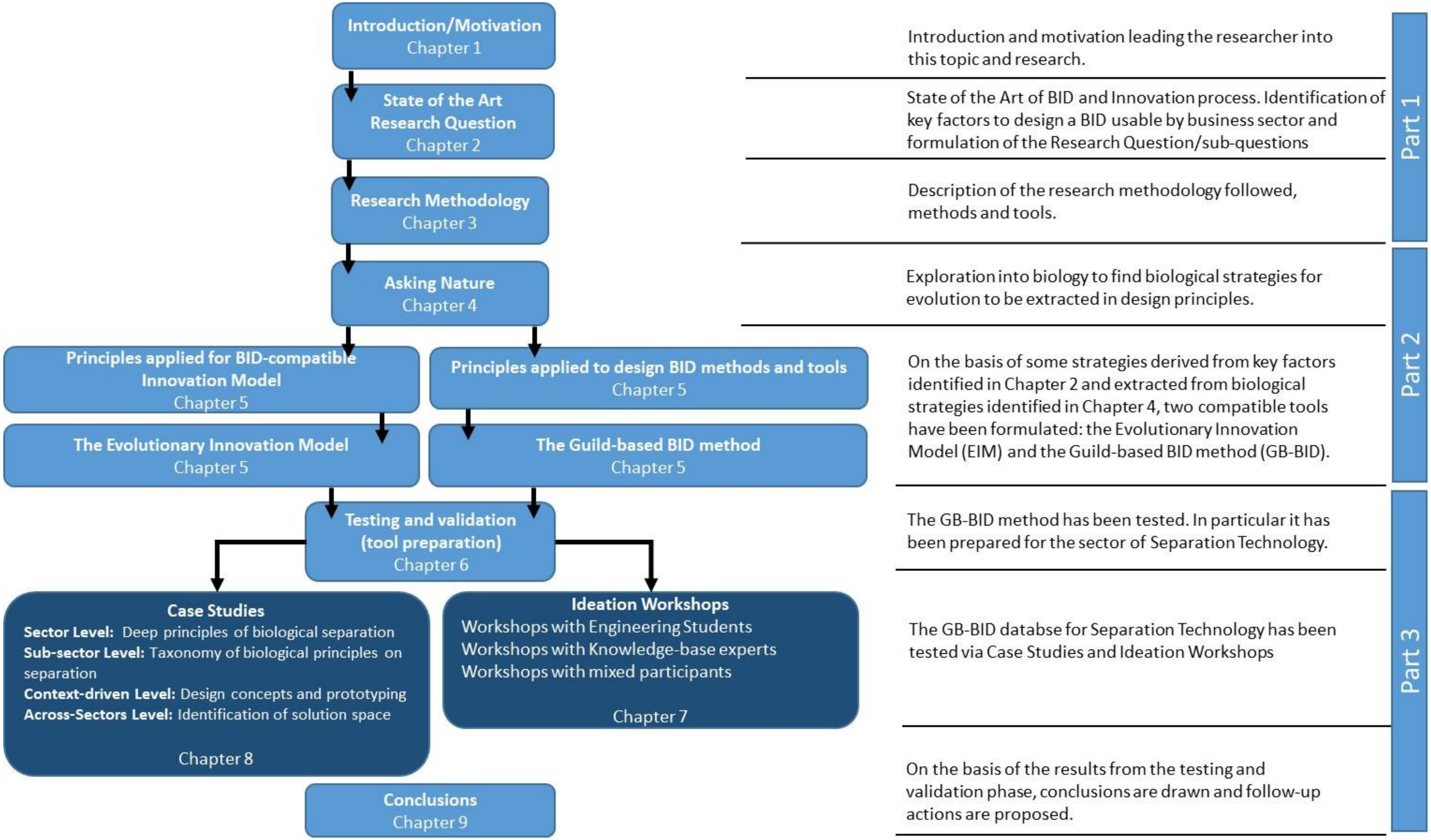



*Figure 1-9: Overall structure of the Thesis*

# 2. STATE-OF-THE-ART

## 2.1 Chapter's structure

As anticipated in section 1.5, the work of this research proceeds through two main working packages: one leading to conceptual products and another one leading to operational products subject to more rigorous testing and validation process.
This chapter aims therefore at providing the essential knowledge upon which both the conceptual and the operational outputs have been developed.
From a procedural point of view, a distinction has been made between the "Analysis of Context" for Innovation processes and the "State-of-the-art" for BID methods, where the former provides the necessary background upon which the conceptual output has been formulated and the latter the starting point from where new knowledge is produced.

Considering that the topics tackled are several, the drafting of this chapter had to take into consideration the following aspects:

- The main body of the thesis should mainly give account of the process which led to the generation of new knowledge starting from the state-of-the-art;
- The volume of information provided should be manageable for a reviewer and focusing on most relevant aspects.

For this reasons a more extensive analysis of the contexts related to both Innovation process/management and BID has been confined in Annex 1. In this present chapter, only the summary of the relevant elements are reported upon which the Research Question has been formulated and are object of the following chapters of the research. For each element, reference is made to the related sections of Annex 1, where, in case of interest, more information and references utilized are provided.

## 2.2 Innovation process and management – Context's Analysis

### 2.2.1 Attributes of the Innovation process

Innovation is a broad concept involving several stakeholders from several domains of knowledge as well as flows of physical resources in space and time. This complexity and diversity leads to different perspectives to innovation, thus resulting in different understanding of the concept (Mitasiunas 2010)
In the attempt to frame in a coherent way the various concepts related to the flow of the innovation process, in order to be useful to this research, the analysis made by Baregheh et al. (Baregheh, Rowley, and Sambrook 2009) has been followed. The Table 2-1 below, expanded and adjusted on the one presented by Baregheh et al. presents these attributes including the words which more frequently have been associated to a specific attribute (see also section 1.A.1 of Annex 1).

| Attributes | Words associated with attributes | Description | Reference to Annex 1 |
|---|---|---|---|
| **Stages** | Creation (also *ideation*), Adoption, Development (also R&D) Implementation (also *production*) Commercialization | *Refers to all the steps taken during an innovation process, which usually start from idea generation and end with commercialization.* | *Section 1.A.2* |

| | | | |
|---|---|---|---|
| **Type** | Product, Service, Process, Marketing methods, Business models, Organizational methods | *Refers to the kind of innovation as in the type of output or the result of innovation, e.g. product or service.* | *Section 1.A.3* |
| **Means Inputs/ Outputs** | Matter, energy, information, financial flows, HR, creativity, ideas, technology, services, values, knowledge | *Refers to the resources needed to the innovation process to operate through its structures as well as the outputs of the process different from the types of innovation* | |
| **Nature** | New (also *disruptive*), Change (also *radical*), Improve (also *incremental*) | *Refers to the form of innovation as in something new or improved.* To be noticed that "disruptive" has been also included in the attribute "Impact" below as the researcher consider it an attribute not intrinsic of the product, but related to its effect in the market/society | *Section 1.A.4* |
| **Model** | Technology Push, Demand Pull, Coupling, Interactive, Network, Open Innovation | *Refers to the different models of innovation process identified as been developed and followed since the industrial revolution.* | *Section 1.A.5* |
| **System/ Boundaries** | National, Regional, Local, Technological, Sectoral, Eco(system) | *Refers to the complexity of the system that is innovating in terms of its structure, components, relationships and boundaries* | *Section 1.A.6* |
| **Impact** | Disruptive, Sustaining, Sustainable, Social, Inclusive | *Refers to the effect that the innovation has (purposefully or not) on the outside World (people and environment)* | *Section 1.A.7* |
| **Social internal** | Organization, Firm, , Group Unit, Developer, Employee, Workforce, Internal environment | *Refers to any social entity, system or group of people involved in the innovation process from within the organization that is innovating.* | |
| **Social External /Environmental** | Social system, Customer, Policy makers (Government), External environment, infrastructures | *Refers to any social entity, system or group of people as well as environmental factors which can affects the innovation process from outside the organization that is innovating* | |

*Table 2-1: Attributes of Innovation by Baregheh et al. - revised by the researcher (additions in green).*

From the table above, specific topics are highlighted in this chapter because they are more directly considered in the research. The following sections report a summary of the topic highlighting the connection with the research. A more extensive analysis is available in related sections of Annex 1.

- Innovation process's stages – Annex 1 section 1.A.2
- Open Innovation Model and Coopetition - Annex 1 section 1.A.5
- Innovation Management Techniques – Annex 1 section 1.A.8

### 2.2.2 Innovation process's stages

As also described in the Introduction chapter (section 1.3) the process of innovation can be divided into four main stages from the moment of the initial decision to tackle a problem to the final utilization and commercialization of an innovative product solving the problem (refer to Figure 1-2). Actors involved in the process are: Individual Inventors, Universities/Research Centres, SMEs and large Industry and Innovative Start-ups.

The diagram presented in Figure 2-1 aims at representing the involvement of the above actors within the process of innovation. The level of involvement in the different stages of the innovation process (see the fading blue colouring in the diagram) it is ultimately dictated by the level of *uncertainty* (linked

to the availability of knowledge) and its conversion to *risk* and the availability of necessary financial resources to proceed in the process (Tidd J. , Bessant J. 2014).
Inventors tend to operate mainly within the Ideation phase while reducing their effort moving toward the R&D phase because of increased risks (see yellow triangle indicating an increase of risk) due to lack of funding and capacity on how to progress in the innovation process.
Universities and Research Centres primarily operate within both Ideation and R&D phases thanks mainly to public (and sometimes private) funding while connecting with Industry and business sector in general to transfer technology before patenting and the Product Development phase (though patenting it is also done by the Universities).
Start-up companies, depending on their capacity to attract investments, tend to operate from Ideation to Product Development phases but do not have often the capacity to move into Commercialization phase and tend to licence patents to Industry.
Large enterprises and SMEs tend to operate mainly from R&D to Commercialization phase reducing the allocation of resources for an extensive Ideation phase because of the high level of uncertainty. Their strategy is often to structure an ideation and R&D process which allows for incremental innovation of product rather that investing in one that could generate radical ideas. The strategy is rather to start from a lower level of uncertainty (higher knowledge and lower risk of failure) waiting for transferring technology once a proof of concept has been carried out by the Academic environment or acquiring a mature knowledge from a start-up.
The orange triangle on the side of the diagram of Figure 2-1 indicates the increasing knowledge of the challenge to innovate and capacity to access the necessary resources to tackle it. This increases from inventors to SMEs and large industry because of the involvement of the latter throughout the overall innovation process.

**<u>Based on the above considerations, it is stressed the importance of the involvement of large industries, SMEs and Start-ups in the ideation phase in order to increase the chances for new ideas to proceed along the innovation process until the market.</u>** (see red circle in Figure 2-1)

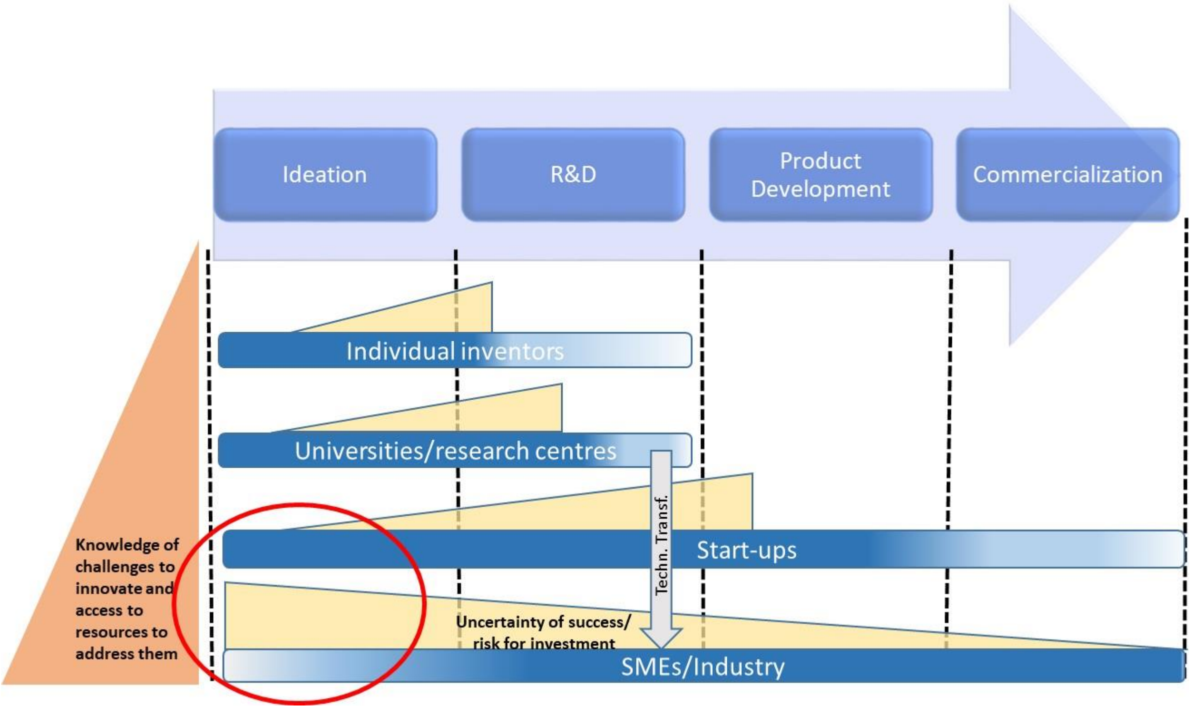



*Figure 2-1: Proposed schematization of the four phases of the process of innovation (ideation, R&D, Product Development and Marketing and selling activity) and the involvement of different entities in them. Explanation in the main text. The overall objective of this research is indeed to increase the involvement of large industries and SMEs and Start-ups in the ideation phase and in particular bio-inspired ideation process. (see red circle in the picture).*

### 2.2.3 Open Innovation Model and Coopetition

Several Innovation models have been identified which have been applied since the 1950-60s (see Annex 1 section 1.A.5). It is worth noticing how they changed through the years: from linear processes, internal to the firm and coordinated by single or few innovation actors (therefore with a low level of complexity), to more non-linear/circular, open/external processes, with many actors involved (therefore with an increased complexity) (see Figure 2-2).

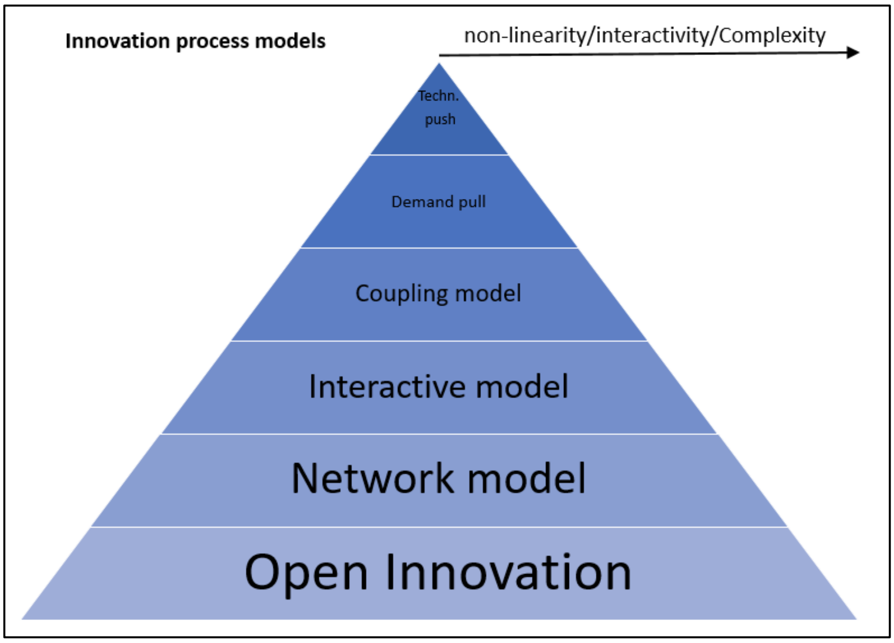



*Figure 2-2: A* proposed pyramid of innovation models which have been developed and applied since the last century from Technology Push to Open Innovation with an increase in non-linearity and interactivity of the model as well as diversity and complexity.

In particular Chesbrough (Chesbrough 2006) defines Open Innovation (OI) as "*the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively*." The OI process therefore combines ideas and knowledge internal and external to the company in order to capture value from the outside.
This shift towards OI models has been substantiated by surveys to European firms over the last years (KPMG 2016; Enkel, Gassmann, and Chesbrough 2009; Cricelli, Greco, and Grimaldi 2016). In particular Cricelli et al. (Cricelli, Greco, and Grimaldi 2016) highlight an increased trend in the use of inbound and coupled OI approaches by EU firms. A KPMG survey (KPMG 2016) shows that organisations with open innovation approach, collaborating systematically for all projects, perform better in innovation development and commercialization. In other words they increase their Innovation Potential (which can be defined as *the ability of firms, in the given circumstances, to effectively use their internal resources, to flexibly respond to external development impulses, and to create and develop activities with a higher added value, thus attaining new, hierarchically higher qualities*.") (Ondrej Z. 2014))
OI has been and can be followed by both large firms and SMEs. In fact as SMEs, differently from large firms, can suffer from workforce shortages, lack of information, of infrastructure and of financial resources; OI has been and could be a way to overcome these barriers (Pellegrino 2017; Kauranen 2016; Lee et al. 2010).
Regarding *partnering*, in a competitive environment, ***Suppliers*** are a very important resource for firms and integrating them effectively in the innovation process will result in improved competitive advantage. The involvement of suppliers could take different forms, ranging from consultation on design ideas to giving them full responsibility for the design of components, systems, processes and services. Furthermore, integrating suppliers in the innovation process to complement internal capabilities will likely lead to reduced time to market, costs, quality issues and improved design effort.

Collaborating with ***Customers*** can increase the ability of a company to innovate and create value, since it allows the firm better understanding customers' needs and expectations and to improve product designs accordingly.
Firms could benefit from the collaboration with ***Universities and Research centres*** to obtain scientific and engineering knowledge to improve their products and processes or if they are aiming at radical innovation (because of the need of new knowledge usually coming from basic/applied research undertaken by these institutions). To be taken into consideration barriers that could arise with this type of collaboration, such as the long-term orientation of academic research versus the focus on short- and medium-term exploitation-oriented research by companies and incompatible reward systems focused on publishing versus protecting results (Pellegrino 2017).
When it is about partnering with ***Competitors*** the concept of "Co-opetition" should be introduced.
According to a survey made by PwC among 1,222 executives in 44 countries (PwC 2017), which assessed the importance of partners in the innovation process, internal employees are considered the most important (60%) followed by: technology partners (50%), business model partners (44%), customers (via focus group, data mining, feedbacks) (35%), Supply chain partners (29%), Academics and research organization (22%) and start-ups (16%).

### *Coopetition*

Co-opetition, has been defined (D. R. Gnyawali 2011) as a strategy embodying *simultaneous pursuit of collaboration and competition* between firms. While firms are competing with each other, they also cooperate to acquire new knowledge from each other.
There can be different reasons why a firm decides to collaborate with competitors, three major drivers have been identified (Miotti and Sachwald 2003; D. R. Gnyawali 2011):

1) Shorter product life cycles, which requires firms to speed-up their innovation efforts.
2) Convergence of multiple technologies, which increases risks and uncertainty about market and technology and pushes firms to reach out to other firms, including competitors, to share the risk and to access and combine a variety of technologies.
3) Increasing R&D and capital expenditures. These provide strong incentives for companies to cooperate with competitors that have a larger resource base. Creating a co-opetitive relationship is an effective way to combine R&D expenses, expertise, and other resources.

Collaboration with competitors has the following main advantages compared to other types of partners:

- Competitors operating in the same market have resources and capabilities relevant to each other;
- Facing similar challenges, joining forces to overcome them is a mutual benefit;
- Potential for generating common technologies due to the similarity of products and possibilities of leveraging resources (D. Gnyawali and Park 2009).

According to Cygler et al. (Cygler et al. 2018) (who conducted a survey on 210 companies operating in the high-tech sector in Poland), the highest benefits in R&D are the acquisition of unique knowledge, development of innovation, and cost reduction. Cooperative R&D is significant in the high investment in technology development but low investment in market development. Companies with such cooperation would work together on innovations, but market the products or services separately. These companies still compete in keeping the market share and getting customers. Typical industries include pharmaceutical industry, biotechnology, automotive and customer electronics (Garraffo 2002).
Cyglet et al. (Cygler et al. 2018) however emphasize also the possible drawbacks of coopetition where one or all the partners misbehave trying to gain more benefits compromising the trust of the others. This can be due to the very nature of the partnership as well as the duration of the cooperation.
Ilvonen et al. (Ilvonen and Vuori 2013) provided an analysis based on reviewed literature about the benefits and risks of sharing knowledge within a coopetitive relationship stressing the importance of

setting up careful management of knowledge sharing ('the act of making knowledge available to others').

As this process of increasing complexity and non-linearity in innovation models progresses, it is detected a certain parallelism with natural systems where organisms, as well as entire ecosystems, increased their complexity of networked relationships and diversity throughout the evolutionary process. More on this will be the subject of chapter 4 and 5, however this initial broad analogy convinced the researcher to explore in more detail such innovation model which more closely mimic the behavior of biological systems.

**Based on the above considerations, it is highlighted the upward trend in utilizing Open Innovation and Coopetition models in various phases of the innovation process.**

### 2.2.4 Innovation Ecosystems

Another relevant concept to be considered in this research is the one of *Innovation Ecosystems*. The concept appears to be a faulty analogy with natural ecosystems (Oh et al. 2016), however taking the following definition from Jackson (Jackson 2011) "*the complex relationships that are formed between actors or entities whose functional goal is to enable technology development and innovation*."
Oh et al. (Oh et al. 2016), through a review of existing academic articles, compare various definitions of innovation ecosystems appearing in different contexts with other classical definition of SI confirming the lack of appropriate differentiations between the two concepts and the lack of a real transfer from the biological analogy. The study also highlights benefits and limits of the use of this concept (see Table 2-2).

| Benefits | Limitations |
|---|---|
| • Motivated successful projects<br>• Encouraged helpful 'systems thinking'<br>• Provided a forum for sharpening some ideas of innovation<br>• Resulted in good press coverage of high-tech regional economic development<br>• May help explain geographical shifts in activity, e.g., from Silicon Valley to Shanghai.<br>• Shows willingness to learn from biological systems. | • The analogy to natural ecosystems is flawed.<br>• Business-only ecosystem contradicts open innovation philosophy<br>• It offers no ready metrics<br>• Suggestions that innovation ecosystems exhibit special kinds of complex system behavior have yet to be substantiated<br>• The term is used in so many ways that no clear definition seems possible |

*Table 2-2: Benefits and Limitation of the concept of Innovation Ecosystem. From (Oh et al. 2016)*

If Oh et al. highlight the flaws in the biological analogy, and the researcher agrees with that, nevertheless he argues it through a rather limited analysis of biological systems.
According to the researcher, the concept of innovation ecosystem, when re-defined following a more robust and coherent transfer of the biological analogy, not limited to the components of the system (and their relationships) but also to their functions, it could become valuable to define new approaches to innovation derived more and more from biological systems.

**From the above considerations, it is inferred that promoting the concept of Innovation Ecosystem could have benefits on the innovation process including learning from biological systems. Furthermore, there is an opportunity to review the current biological analogy of Innovation Ecosystem to propose a more coherent one.**

### 2.2.5 The importance of Ideation phase

Among Innovation Management Techniques/tools, this research puts emphasis on ideation approaches and techniques, which are at the core of the Ideation Phase of the innovation process. It is indeed often assumed that in order to develop their innovation capabilities, firms need to invest to constantly create new knowledge, which can generally be created from new ideas generated either internally or often transferred from other actors in the value chain (suppliers, consultants, etc.) or from research literature (Grimsdottir and Edvardsson 2018).

Ideation capabilities of a company can be seen as managerial and organizational processes for the stimulation, identification, selection and implementation of ideas (Björk, Boccardelli, and Magnusson 2010).

So, who should participate in the ideation process? Especially from the perspective of Open Innovation and Design Thinking (as per IDEO's definition and practice (Johansson 2013; Bjögvinsson, 2012)) it is clear that aside the internal potential, also the external untapped potential of idea sources is becoming increasingly important (Grimsdottir and Edvardsson 2018; Del Giudice 2015; Chesbrough 2006; 2013). To reinforce this consideration, a survey conducted by PwC interviewing 1,222 executives in 44 countries (PwC 2017) was carried out with the goal of understanding how companies' leaders view innovation and what they are doing to improve it. The following findings are highlighted:

- Importance of bringing more parties, including customers, into the innovation process at the ideation phase to improve strategic alignment, to access fresh ideas and critical talent, to failing faster and getting new innovations to market sooner.
- Importance and struggle to bridge the gap between innovation strategy and business strategy. This could be overcome bringing people from the business-strategy side, such as firm's managers, at the ideation phase of any new, potential innovation.
- The most followed innovation models utilized to drive innovation are: Open Innovation (61%), Design Thinking (59%), Co-creating with customers, partners, suppliers (55%), traditional R&D (34%), innovating in emerging markets (34%). Other models such as internal incubators and investing in start-ups via corporate venture capital are utilized less (below 30%).
- Adopting Open Innovation and Design Thinking, especially by larger companies, helps bringing together people from across the company's various areas of expertise (ex: through workshops). This is something that smaller companies are often able to do with greater ease and frequency.
- The main factors influencing successful innovation are: innovative behavior and culture (65%) and fresh ideas (63%); increasing budget for innovation is considered of a lesser importance (32%).

**On the basis of the above considerations, it is highlighted the upward trend of the importance of the ideation phase within the overall process of innovation as well as the call for more inclusiveness of actors previously excluded from this process.**

### 2.2.6 Issues on Innovation process and management addressed in this research

Based on the analysis reported above, this research aims at addressing the following issues which can improve the connection between BID and the Industrial/business sector:

1. Well-established SMEs and large industries as well as start-ups are the actors within the overall innovation process with presence in and knowledge of the full process, from problem definition to commercialization of product. Their increased involvement in the ideation process would increase the chance to have ideas turning into marketable products.
2. Creativity development/Ideation approaches and techniques, which include BID methods, are recognized as tools for nurturing innovation which can help firms to foster competitive advantages.
3. Application of Networked, Open and Coopetitive models of innovation is an upward trend highlighting the need for a multi-stakeholder approach to innovation where different actors

from within and without a firm cooperate in the process of innovation, including the ideation process.

4. The participation to the ideation process of managers and other actors involved in the overall innovation process would allow for a more effective selection and integration of relevant ideas within the overall innovation process.
5. Promoting and applying the concept of Innovation Ecosystem could generate benefits to the overall innovation process including increasing learning from biological systems. The concept would benefit from a review in order to align it to a more coherent biological analogy.

## 2.3 BID methods and tools – State-of-the-art

### 2.3.1 Brief Introduction to BID Methods and Tools

Biologically-Inspired Design (BID) methods and tools belong to the category of Ideas generation approaches defined "Design-by-Analogy" (DbA). Analogy, in the context of design, is defined as the process of association between situations from one domain (source) to another (target) through the establishment of relations or representations (Gentner, Rattermann, and Forbus 1993). Designs are analogous if they share at least one function or behavior, but not necessarily similar structures. In the case of BID, the analogies come from the domain of Biology.
For a more extensive introduction of Ideas generation methods and Design-by-Analogy, Annex 1 section 1.B.1 and 1.B.2 can be consulted.

The potential of BID methods lays in their capacity of producing stimuli to the designers derived from the biological analogy. As in all DbA, also in BID the distance of the analogy has an important role to play in the generation of ideas. Breakthrough innovations are more likely to result from far analogies between distant domains (Herstatt and Kalogerakis 2005).
Furthermore, biological solutions, following principles different from technological solutions, could allow the designers to access different and unusual solutions.
For a broader description of BID methods and tools, please refer to Annex 1 section 1.B.3.

BID methods have been developed by different research groups and organizations (see reviews in (Wanieck et al. 2017; Fu et al. 2014; Fayemi et al. 2017)) and they follow two main broad approaches: the *solution-driven* or *problem-driven* approaches.
Solution-driven when a biological knowledge of interest stimulates the solution of a specific technical problem.
Problem-driven starts with a challenge to be solved and a search into biological knowledge for solutions. Several authors define the same dichotomy with other terms such as *Mechanism driven/Organism driven*, *Top down/Bottom up*, *Technology pull/Biology push*, *From challenge to biology/From biology to design* (Helfman Cohen and Reich 2016)
In this research a six steps problem-driven process and seven steps solution-driven process are considered as per Helm et al. (Helms, Vattam, and Goel 2009a) with additional considerations when deemed necessary (Table 2-3 and Table 2-4):

| Problem-driven approach's steps | Description |
|---|---|
| 1. *Problem definition/analysis* | Selection of a problem to solve and performing further definition of it through functional decomposition and optimization. |
| 2. *Reframe the problem* | Redefining the problem using broadly applicable biological terms. Asking the question: "How do biological solutions perform this function?". It can |

| Problem-driven approach's steps | Description |
|---|---|
| | be also defined with "Transposition to biology"(Fayemi et al. 2017) or "biologizing" the question (Baumeister and et Al. 2011) |
| 3. *Biological solution search* | Selection of biological model(s) of interest. Find solutions that are relevant to the biological problem with techniques such as "changing constraints" so as to expand or narrow the biological search, "analysis of natural champions of adaptation", "variation within a family of solutions" and "multi-functionality".(Helms, Vattam, and Goel 2009a). Tools such as AskNature can be utilized as well as consulting biologists. |
| 4. *Definition of the biological solution* | The biological solutions identified need to be understood in detail.<br>Some authors refer to this step also as "Abstraction" as the process of refining the biological knowledge to some working principles, strategies or representative models that explain the biological solution and could be further transferred to the target application (Helfman Cohen and Reich 2016). These models should explain how the problem is solved in biology and may include references to functions, structures, behaviours, principles or strategies in case they are related to the solution.<br>Baumeister et al. (Baumeister and et Al. 2011) considers this step as part of the Abstraction of the Biological Strategy step: *"The abstracting step includes two components: distilling the biological mechanisms and translating them to design principles."* |
| 5. *Principle extraction* | After a solution is understood, relevant principles are extracted into a "solution-neutral" form, which required a description that removed as many specific structural and environmental constraints as possible. (Helms, Vattam, and Goel 2009a)<br>Baumeister et al. (Baumeister and et Al. 2011) combine this step (design principle extraction) within the broader step of Abstraction of the Biological strategy: *"abstracting is the translation from the biological mechanism to a design principle…During the abstraction stage, the bridge between biology and technology is built and the biological solution has to be presented in non-biology language but in language that allows a designer/engineer understanding and utilizing it*." |
| 6. *Principle application* | After the principle is extracted from the biological solution, designers transfer the principle into the new domain. This transfer involves an interpretation from one domain space (e.g. biology) into another (e.g. mechanical engineering), by introducing new constraints (and affordances) to the biological problem (Helms, Vattam, and Goel 2009a).<br>Design concepts can be generated. This activity will culminate in the embodiment of a bio-inspired solution of a technological product or system.<br>In other authors, Principle Application seems corresponding to the "transposition to technology" (Fayemi et al. 2017; Sartori, Pal, and Chakrabarti 2010; Helfman Cohen and Reich 2016) |

*Table 2-3: Steps of the Problem-driven approach.*

| Solution-Driven approach's step | Description |
|---|---|
| *1. Biological solution identification* | From the observation of natural phenomena on a macro scale and / or a micro level, a potential solution to apply is sought to transfer to a human problem. (inspirational organisms) |
| *2. Definition of the biological solution* | As per step 4 of the problem-driven approach |
| *3. Principle extraction* | As per step 5 of the problem-driven approach |
| *4. Reframe the solution* | Reframing forces designers to think in terms of how humans might view the usefulness of the biological function being achieved. (in technology terms) |
| *5. Problem search* | Whereas search in the biological domain is confined into some finite space of documented biological solutions, this search may include defining new problems (this is much different from the solution search step in the problem-driven approach). |
| *6. Problem definition* | By analogy with the definition of the biological solution, the problem is outlined similarly. The aim is thus to establish a parallel between the system, components and mechanisms of the biological solution and the problem. |
| *7. Principle application* | Once the solution principle is established, it is transformed into a working principle of the technological concept that is needed. Design concepts can be generated. This activity will culminate in the embodiment of a bio-inspired solution of a technological product or system. |

*Table 2-4: Steps of the Solution-driven approach.*

### 2.3.2 BID's Key Factors

Based on the considerations already highlighted especially in section 1.4, and section 2.2.5, there is a need to bridge some gaps between BID and the industrial/business sector in order to increase the chances for bio-inspired ideas to become innovation and reach the markets. In order to start selecting topics to be more specifically addressed by this research, it is considered useful to carry out an analysis of the context based on the following *Preliminary Research Question*:

***Which are the key factors to be considered when developing a BID method to make it usable by the business sector?***

This question has been answered through a review of relevant scientific literature as well as on anecdotal considerations based on the experience of the researcher (duly highlighted when occurring).

From the above review that concerned more than 200 papers (see references in Annex 1), it was found that the review made by Fu et al. (Fu et al. 2014) on challenges around ideation processes (BID and non-BID) was the most comprehensive and it was chosen as main reference to be followed. Its framework is organized into *factors* and related "*take-aways*" which in this context have been renamed "*considerations"*. Considerations are of both positive and negative nature. Additional factors taken from other authors are cited as needed.

The *Cognitive* and *Implemention* factors identified by Fu et al. have been re-organized and expanded into three main clusters of *Key Factors* and their respective sub-categories (see Figure 2-3):

1. *Key Factors in generating ideas (*cognitive factors*)*: Design fixation, Incubation, Memory, Analogical Reasoning Processes, Modality in Representation, Analogical Distance, Commonness, and Expertise. These factors and considerations have been recognized valid for the overall process of ideation.

2. *Key Factors in generating bio-inspired ideas* (cognitive and implementation factors): Cognitive aspects, Accessibility, Computational Synthesis/Automation, Problem/Solution-driven approach. These factors and considerations have been recognized valid for the specific BID process.
3. *Key Factors in bringing bio-inspired ideas to the market* (implementation factors): these are the main factors influencing the adoption of BID method for ideation process by the industry and hampering the progress of bio-inspired ideas to the next phases of the innovation process until commercialization.

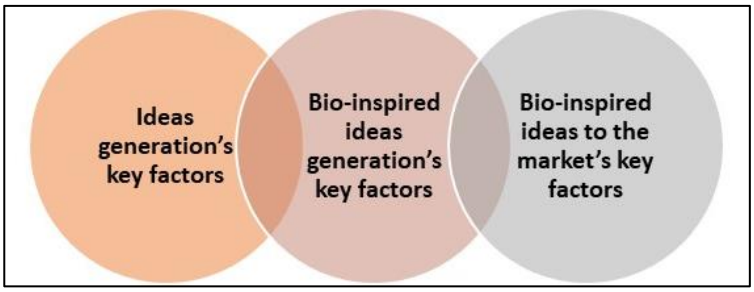



*Figure 2-3: Clusters of key factors from ideas generation to bio-inspired ideas to the market. They sometimes overlap.*

*Table 2-5: Key Factors in ideas generation's process.*

| Key Factors | Considerations |
|---|---|
| **Design Fixation**:<br>"Blind adherence to a set of ideas or concepts limiting the output of conceptual design" (Jansson and Smith 1991) | • Designers do not have control over or awareness of when, how, and upon what they fixate.<br>• Training, area of expertise, and experiences with existing concepts/ artifacts can change how one fixates.<br>• Incubation can break fixation.<br>• Multiple representations and re-representation of the design problem can help to break fixation.<br>• There are mixed reports of the fixation effects of physical models.<br>• Fixation is not always necessarily a bad thing. Ex: Having designers copy examples that they could not understand assisted them in finding a new representation of the information in order to understand it. |
| **Incubation**:<br>A period of problem solving that occurs after initial failed attempts to solve a<br>problem and after which an insight occurs suddenly and, perhaps, unpredictably,<br>allowing to reach a solution(s) | • Incubation is effective in helping designers overcome impasses.<br>• Incubation helps designers apply relevant information to solve their problem.<br>• Incubation is expressly linked to fixation and memory, and has interaction effects with distance of analogy. |
| **Memory**:<br>The mental capacity to recall previously learned information or knowledge | • Unassisted cross-domain transfer of knowledge is difficult to achieve due to specific expertise and memory as designers working in teams draw on their personal knowledge.<br>• Memory and distance of analogy are linked – memory effects impede far-field analogies (too difficult to be noticed or to be retrieved in memory).<br>• There are ways to work with the properties of memory to facilitate design-by-analogy if the analogy is encoded into memory in a way that allows key relationships to be applied to both source and target domains. |
| **Analogical Reasoning Processes**:<br>The cognitive steps and characteristics that humans employ when working to find/retrieve, | • Analogical reasoning processes have been characterized by the phases (ex: retrieval, mapping, and evaluation), influencing factors, constraints (ex: psychological ones) and purposes served (ex: identifying problems, communicating concepts, and solving problems). |

| Key Factors | Considerations |
|---|---|
| translate/abstract/transfer and evaluate information/knowledge being mapped from a source application to a target application | • In the context of ideation, metaphor is distinct from analogy. Metaphors are used to frame the problem and understand the design situation; analogies are used in the conceptual design phase to map from source to target.<br>• Types of analogical transfer can be characterized in multiples ways, but broadly speaking, range from surface level (ex: transfer of technology from one domain to another) to deep analogy (inspiring ideas). |
| **Modality in Representation**: The form that an example or (analogical) stimuli might take on, corresponding to the variety of sensory perceptions that might be involved in processing them | • Too much superficial detail, which tends to be true of (i.e. detailed prototypes),in representation of analogical stimuli within-domain can have negative effects on design outcomes restricting retrieval of far-field analogies from memory.<br>• Some researchers found visual analogies to be most beneficial to design.<br>• Others have found that text based stimuli is most beneficial to design.<br>• Still others found that multiple modalities were best for design. |
| **Analogical Distance**: Conceptual distance between the source and target of analogy | • The larger faction of researchers argues that far-field analogies are most beneficial to innovation in design.<br>• Other researchers disagree that far-field analogies are always most beneficial.<br>• Others found that benefits of analogical distance depend on other factors, and neither near nor far-field are necessarily always best. For instance the time of introduction of the stimuli can be a factor as well as identify a "sweet spot" of analogical distance, where "too near" analogies may be trivial or fixating, and "too far" analogies may be difficult to usefully apply to the target domain. |
| **Commonness**:<br>How often the analogies are found in designers' worlds and design environments, or how familiar designers are with an analogy. | • Less common stimuli were found to be more beneficial to design than more common stimuli.<br>• Some researchers disagree, finding an inverse correlation between commonness and probability of fixation. |
| **Expertise**:<br>The level of experience, training, and knowledge that a designer has with respect to a particular field, practice (design), or tool | • Novices show distinct differences from experts in design-by-analogy execution, and generally have more difficulty with it.<br>• In different and particular domains of knowledge, experts and novices use analogies differently.<br>• Generally, across fields, experts demonstrate behavior that leads to more success in design-by-analogy.<br>• Novices and experts are similar in some respects, including benefiting from visual analogies and susceptibility to fixation, however experts can produce more non-redundant ideas and can mitigate their fixation with the help of de-fixation materials. |

*Table 2-6: Key factors in BID's process*

| Key Factors | Considerations |
|---|---|
| **Cognitive aspects :** cognitive mechanisms that are unique to bio-inspired design | • Designers and novices in particular, have difficulty abstracting strategy level principles during BID, showing particular susceptibility to fixation on superficial details. In particular:<br>○ Students had difficulty in mapping analogies from biology to engineering domain, fixating on applying strategies only to specific parts of the design problem; more generalized descriptions of biological phenomena could help with transfer;<br>○ Designers fixate on irrelevant superficial content of biological knowledge when mapping, and had difficulty identifying the relevant analogy;<br>○ Novice designers tended to map specific features of stimuli, as opposed to identifying an overall analogy and employing it in multiple ways |

| Key Factors | Considerations |
|---|---|
| | ○ Abstraction of biological nouns led novice designers to fixate on other non-abstracted words, e.g., verbs in text descriptions, and reduced ability to understand biological phenomena. |
| | • BID outcomes are affected by aspects of design-by-analogy, including distance of analogy, modality of representation, and expertise, and many others. In particular:<br>○ Success of BID is highly influenced by the designer's own prior knowledge of biology, which can both help or hurt the process.<br>○ Biological examples improved novelty without inhibiting variety; far-field biological examples led to more successful higher levels of abstraction, believed to cause greater variety; near-field and far-field biological stimuli both caused fixation, with near-field participants fixating on surface and structural aspects; far-field participants fixated on structural aspects.<br>○ Investigations on how different modes of representation affect the nature of design outcomes in the context of bio-inspired design highlight that non-verbal-images first and verbal-textual later, are the more effective |
| | • Analogical reasoning processes and aspects of the mechanics of using BID in problem solving have been explored, uncovering deeper mechanisms to study. In particular:<br>○ In a BID course, analogies were used in almost all phases of design process; analogies classified into five types: direct transfer, schema induction, problem transformation, deferred goal, and compositional analogy;<br>○ 5 main design activities to code BID data: problem discussion/analysis, biological phenomenon discussion/analysis, relating to/recalling existing solutions, generating new solutions, and evaluating solutions/analogies;<br>○ Design evaluation and critical thinking led to strategy level analogies from biology, as opposed to lower level superficial or function analogies;<br>○ Three key attributes of evolution of design problem; (1) design problem can/may change throughout design process, regardless of success/failure of ideation activities; (2) Existing solutions to design problem affect how it is formulated; (3) value of cross-domain analogy/knowledge transfer not only comes from transferring concepts, but also innovative design problem formulation |
| | • Strategies and recommendations for how to (and how not to) best perform and teach BID have been suggested based on the literature.<br>○ To teach BID to undergraduate of engineering and biology majors, familiarize students with techniques to help transfer knowledge from biological to engineering domain through lectures on BID practice and examples, analogy exercises, mentorship, and more.<br>○ Directed method for BID had no benefit to design outcomes when compared to using no formal ideation method;<br>○ Provide thorough account of cognitive challenges when performing BID, including difficulties with retrieval, inaccurate mental models, improper feature transfer/focus, ignoring of distant analogies, and fixation. Future BID methods/tools should encourage designers to develop multiple concepts based on each biological source, present diverse stimuli with shared underlying principles, provide uncommon solutions, incorporate structures of categories of the information, and provide abstractions of the biological information. |
| **Accessibility:** How available the tool or method is to the academic or public community for use. | • Knowledge-based BID tools are not always accessible (Ex: IDEA-INSPIRE) and when accessible their content is not necessary useful for solving specific problems (Ex: DANE with 22 entries). The most accessible and rich in entries is AskNature.<br>• Lack of accessibility reduce diffusion of and awareness around BID as well as confidence in the effectiveness of the BID methods and tools to generate innovative ideas. |
| **Computational Synthesis/Automation:** How automated the solving of the | • Most of the methods/tools do not attempt to automate the design process (ex: Engineering-to-Biology thesaurus), though some are more automated than others (ex: IDEA-INSPIRE, Natural Language Approach to Biomimetic Design and AskNature).<br>• None of these automated tools suggests solutions to design problems or evaluate how useful/helpful each piece biological might be. |

| Key Factors | Considerations |
|---|---|
| design problem is using the tool/method, or how much human input/work is required to reach a result. | • It is also not explored the time and cost occurred to create and scale up such system.<br>• Scalability. Searching large repositories of biological strategies, such as AskNature, requires a scalable, automated approach that allows the identification of a number of candidate biological strategies to be considered in the next step. (Vandevenne et al. 2011)<br>• Expandability. The tool should be able to be scaled-up with new biological entries to provide analogies for new specific problems. |
| **Problem-driven, Solution-driven approach** | • The existing BID methods and tools do not necessarily all facilitate both problem and solution driven approaches. |

*Table 2-7: Key Factors in bringing bio-inspired ideas in the business sector and to the market.*

| Key Factors | Considerations |
|---|---|
| **Awareness and managerial support** (PwC 2017) see section 2.2.5 | • Despite BID, under its different definitions (biomimetics, biomimicry, bionic, etc.), is spreading among the industrial environment, its methods, successful case studies and measured impacts are not. The topic is largely treated in journals and conferences specialized in Design and BID which are not normally consulted and frequented by the industry, which rather concentrates on sectoral publications and conferences.<br>• Participation to the Ideation Phase of firm's managers and other non-technical stakeholders would increase the chance to move new design concepts through the innovation process. |
| **Multi-disciplinarity in design team**<br><br>(Jacobs, Nichol, and Helms 2014) | • Bio-inspired ideation process in firms is carried out largely without biologists and with teams of maximum two disciplines (ex: engineering and chemistry). This can:<br>  ○ Limit the exploration of biological solution and their understanding with difficulties in transferring to technology (extracting useful design principles);<br>  ○ Prevent addressing the complexity of a problem with consequent generation of solutions which are ill-designed and therefore with less chances to be considered for further development. |
| **Scalability of biological mechanisms** (Helfman Cohen and Reich 2016)-section 1.8 | • Some biological mechanisms work at the nano scale but fail to work on macro scale where their technological applicability would be expected and could generate interest by the business sector.<br>Example is the gecko attachment mechanism. Synthetic mimics of the gecko's attachment system have failed to show adhesive performance at larger scales. |
| **Material constraints**<br><br>(Helfman Cohen and Reich 2016)-section 1.8 | • Sometimes there is no artificial substitute for the biological material. Mainly when the function is more related to the given material and less to the structure. One example is the spider silk. Although its molecular structure is known, the scientific world struggles to synthesize artificial materials that could imitate the structure and maintain its unique characteristics. This limits the interest of the business sector. |
| **Manufacturing constrains** (Helfman Cohen and Reich 2016)-section 1.8 | • Lack of suitable manufacturing processes is one of the major restriction on delivering biomimetic innovations. For example, the lotus leaf-inspired artificial products are still far from the biological model's performance. |

### 2.3.3 BID methods in the business sector

With the promise of assisting the process of product innovation, BID is aiming at becoming a streamlined approach in the ideation process. The goals of the academic sector is to develop more effective BID methods and tools and to train students of various disciplines connected with Product Development representing the future generations of engineers and designers who will work within and for the industry. It is of course not guarantee that BID will be utilized in their future profession.
The efforts of bringing BID directly from academic environment to the industry seem fragmented. BID literature is abundant of researches highlighting experiments with university students of engineering, design, sometimes biology (Graeff, Maranzana, and Aoussat 2019; Farzaneh 2016) and architecture

(Zari 2010). From a rigorous methodological point of view, testing BID methods with students it is appropriate because they may have fewer preconceived notions of possible solutions to problems and therefore the analogical matching of biological phenomena to solutions results less biased (Mak and Shu 2004) and also to guarantee accessibility to consequent samples in experiments (Graeff, Maranzana, and Aoussat 2019).
On the other hand, it is rare to find scientific literature mentioning testing of BID methods with representatives from the business sector or also defined as *knowledge-domain (-based) experts*. (Kennedy and Marting 2016; Helfman Cohen and Reich 2016; Moreno et al. 2015)

Also in the words of Goel et al. (Goel, McAdams, and Stone 2014) *"…BID remains largely a research activity contained in universities. BID is not yet an activity practiced by design engineers in the field. This ''research-not-practice'' status of BID exists because most BID is the result of researchers studying a biological entity or system such that their level of understanding allows an almost direct emulation but not necessarily new inspiration. This point solution status of BID sets a large, if a little ill-defined, scope for BID research: How do we transform BID from a point solution effort to fundamental theories and methods?*"

These facts open for a reflection on the impact achieved so far by BID for innovation. Claiming that BID improves metrics of ideas generation does not implies that these improved ideas will reach the status of innovation as the path from ideas to innovation is far from being straightforward. Account in scientific literature is not frequent for bio-inspired ideas (generated from a BID method) that succeeded to reach at least a pilot testing stage in industrial environment.
As a speculation, the reasons for this lack of studies could be:

- an objective difficulty in conducting meaningful research at industrial level due to the disconnection between scientific and industrial community;
- lack of interest of the industry in sharing information on product development with the scientific community.

As already highlighted in chapter 1 the most exhaustive research identified by the researcher, which analyses claimed bio-inspired products and archives them in a database – BioM – it is the one conducted by Jabobs and Helm (Jacobs, Nichol, and Helms 2014). They argue that the analysis of BID in professional practice has focused so far only on post hoc reporting of case studies, without theoretical analysis of the processes and products of professional BID practitioners. To respond to this lack, the authors (as already reported in chapter 1) gathered information of almost 380 claimed bio-inspired projects in industrial environment. From their analysis, also partially re-elaborated by Chirazi et al. (Chirazi et al. 2019), the following aspects are highlighted:

- 70% of the BioM products did not make it to the marketing phase, as they were still in development, a concept, or already discontinued;
- 95 cases resulted in patenting;
- ~31% were commercially available, ~58% were in development (prototype phase), ~8% were unpatented concepts, and ~2% were discontinued;
- It turned out that 26% of commercially available products were not biomimetic, showing that marketing departments are beginning to adopt the bio-inspired brand, increasing consumer awareness, but also potentially diluting the value. To such an occurrence, ISO is attempting to regulate the branding through its Standard: BS ISO 18458:2015 "*Biomimetics — Terminology, concepts and methodology*".

The study however does not report on the BID methodology utilized by the firms, making an assessment on the effectiveness of BID methods in industrial environment not possible.
Another outcome from the study is that on 66 firms interviewed, 75% answered that the products were developed using the solution-driven approach in contrast to the problem-driven approach.

The authors does not elaborate on this, but according to the researcher, this can be an indication of the non-use of structured BID but counting on moments of serendipity (also considered by (Wanieck et al. 2017)). The solution-driven approach is a more “intuitive” approach to bio-inspiration; getting inspired by biological phenomena and abstract them to generate technological solutions. For established firms, having a well-defined core business, a BID problem-driven approach could be of more use; Jacob’s study reports 25 firms having potentially utilized such a method.

Most probably because of confidentiality reasons, it is also hard to gather meaningful data regarding the use of BID methods by academicians within industrial context; such as in contracts of cooperation between Universities and companies.
The researcher is aware about the Politecnico di Milano and the Ecole Polytechnique Fédérale de Lausanne (EPFL) cooperating with companies in specific bio-inspired design challenges availing of students to work on specific problems provided by the companies.
Cooperation of industry with external consulting/design companies specialized in BID is also difficult to trace due to confidentiality issues.
To the best knowledge of the researcher, the Biomimicry 3.8 (biomimicry.net) is the most successful consulting firm in the sector of BID. However, the company, mainly composed of biologists, assists the clients in helping abstracting the problem in biological terms, exploring nature for relevant biological champions and proposing to the clients extracted biological principles. It is usually left to the client to extract design principles for its own purposes (this information derived from personal knowledge of the researcher who studied at the Biomimicry 3.8).
The Biomimicry Institute (biomimicry.org), a no-profit organization, organizes every year, since 2008, the so-called *Global Biomimicry Design Challenge*. This competition, open to team of students or professionals worldwide, calls for proposals of bio-inspired solutions to global challenges (such as Water scarcity, Sustainable Transport, sustainable Food cycle, Climate Change, etc.). The competition is not linked to any particular company (though the major sponsor is the Ray Anderson Foundation linked to the US-based company Interface).
Every years some hundreds of teams submit their ideas and following and evaluation process which assesses not only the feasibility of the solution proposed, but especially the process followed from the biological search to the extraction of design principles from biological systems. The methodology proposed is the Biomimicry Thinking, combined with the use of AskNature. The finalist teams get access to a business incubation program to further develop their idea to reach the prototype phase. At that stage, the finalists compete for the final prize. Some of the finalist teams continue to develop their products and in some cases, they open dedicated start-ups (the researcher is one of them, co-founding the start-up Planet s.a.s). Following an interview with staff of the Biomimicry Institute in October 2019, none of the finalist products developed during the Design Challenge (24 from 2015 onward) reached the market while five of them are currently in an advanced pilot-testing phase.
The Global Biomimicry Design Challenge is nowadays the most known and widespread action related to BID.

**From the above analysis, with many uncertainties due to lack of significant statistics, it is inferred that BID methods and tools are not yet systematically introduced in industrial environment but remain confined in Academic environment. This may prevent bio-inspired ideas to reach the market.**

### 2.3.4 Biological quantity/quality vs Problems vs Costs

*Biological quantity/quality*

One of the challenges of BID is the access and understanding of biological knowledge (natural solutions) so that designers can utilize it with effectiveness.
Three main approaches emerge from literature among the possible strategies to allow designers and technicians to access and use the knowledge about biological systems described in the biological

literature: the *Database* approach, the *Text-Mining* approach and the *TRIZ* approach. (Baldussu and Cascini 2015).
The Database Approach aims at creating a collection of biological effects/phenomena classified by a specific functional taxonomy. One examples is AskNature (http://www.Asknature.org/).
The Text-Mining Approach has the objective to exploit large amount of biological knowledge available in books, journals, etc. without the necessity of creating and maintaining large databases. Difficulties may derive from the difference between the language adopted by biologists and engineers.
Vincent et al. (Vincent et al. 2006) used TRIZ as a set of procedures and tools to generate technical systems imitated from biological systems and developed the Bio-TRIZ Matrix derived from the TRIZ Matrix of Contradictions.
Other approaches such as the one followed by Nagel et al. (J. K. S. Nagel, Stone, and McAdams 2010) somehow remove the problem of searching into biology proposing stand-alone functional basis of biological terms.
To be highlighted that the literature consulted on BID does rarely refer to consultation with biologists, and if it does, it does not report in detail on any structured method for consultation, which could become part of an experiment or a BID methodology.

Because of these different approaches to gather biological knowledge, different BID tools have different level of quantity and quality of biological knowledge available and/or accessible.
The entries of AskNature database, despite their amount (1750 at 05/2020), and their categorization according to the Biomimicry Taxonomy, varies largely in terms of quality. The detailed description of the organisms and their functions are extracted from: biology related scientific articles, reports of consultancies made by Biomimicry 3.8, Life Science Text books, dialogues of Nature's documentaries (ex: extracted from documentaries of Sir David Attenborough). Information can be visual (photos, drawings, videos) sometimes schematizing the biological mechanism, and textual. Sometimes the entries are rich in scientific references (not necessarily open access), sometimes not. This variability in quality may affect the results of the BID process as the relevant biological process may not be described in such a detail to be useful and further research is definitively needed.
Furthermore, because of the organization according to the hierarchy of the Biomimicry Taxonomy, the same organism may have multiple entries of the database according to the biological solution (function) explored. For instance, the beak of the toucan has one entry for its capacity to dissipate heat and another one to resist impact dissipating energy through its trabecular structure. Only typing "toucan" in the query box one can access both functions. In this way both problem-driven (starting from the function) and solution-driven (starting from the organism) approaches can be possible.

The biological entries currently proposed by SBF-DANE (Goel, Rugaber, and Vattam 2009), only 22, seem derived from mixed sources including scientific literature and Life Science Text Books. Obviously, the limited number of entries (and functions) does not allow for addressing a large variety of challenges. On the other hand, the scope of DANE is rather to propose an ontology for biological modelling and it is left to the users to populate the database (though the encoding functionality has not been activated yet).
The same is valid for IDEA-INSPIRE (Chakrabarti et al. 2017; and 2005), whose database is not accessible. However, from the description in literature, the biological solutions seem encoded with richness of detail for each entity of the SAPPhIRE ontology.
The database of Find-Structure (http://findstructure.org/), another recent method developed by Cohen et al. (Helfman Cohen, Reich, and Greenberg 2014b), is based on 140 biological solutions and organized according to function-structure patters. It provides an abstraction in the form of structural patters solving certain functions and a brief description of the biological structure and functioning.
BioTRIZ (Vincent and Mann 2002; Vincent et al. 2006; Bogatyrev and Bogatyreva 2009) has been developed analysing some 500 biological phenomena, covering over 270 functions, encoded in a dedicated database which however is not accessible.

Other methods such as the Function-based BID and Engineering-to-Biology Thesaurus (J. K. S. Nagel, Stone, and McAdams 2010) have been developed, as reported by the authors, impinging into Life Science Text Books. According to the authors, a database has been created for the function-based BID. However the researcher could not find access to it, neither its description.

Few researches have been identified about comparing metrics of the ideation process among different BID methods solving the same problem. For instance, to assess how the representation of the biological information, their quality and quantity influence the metrics. (the work of R. Tan on comparing BID ontologies (Tan et al. 2019) and one of his paper currently under review addressing this metrics comparison but with partial results, have been the only references found).

**From the above analysis, it is inferred that the importance of the quality and quantity of biological information for BID purposes has not been properly researched even if it may play a relevant role in the outcomes of the BID process.**

*Problem-based BID*

Because BID methods and tools are generally conceived to assist to solve all sorts of technical problems, they are *decoupled from specific context*. To the best knowledge of the researcher, there have not been studies attempting to "*customize*" the BID method for specific problems, to make it *problem-based,* or to carry out sensitivity analysis of BID methods vis-à-vis formulated problems.
It is plausible to consider not very relevant to conceive a problem-based methodology when the de-contextualized/universal ones existing have produced results and have not been challenged on this aspect. Furthermore, as BID methods are appreciated for and evaluated on their capability to remove design fixation and open up to more, more diverse and more novel ideas, trying to limit their potentiality imposing more constraints requested by a *customization* or *contextualization* may result in narrowing the solution space.
It is however important to reiterate that, so far, the applicability and effectiveness of BID methods have been tested mostly in academic environment, on students. Therefore with agents who do not have yet any specific competence in any specific business/industrial sector and who are requested to solve often tailor-made challenges identified by tutors (not necessarily coming from a specific request from an external firm) and an uncertain level of motivation in doing that (as commented also by Yen et al. (Yen et al. 2014)).
What happen when the problems are proposed by firms? For business reasons they may request the BID method to deal with problem formulation of different complexity and contextual details. Different level of abstraction. For instance, they may ask to generate ideas for:

- "a new filtration system for water", or
- "a new filtration system for water which removes particle of a certain size", or
- "a new filtration system for water which removes particle of a certain size that does not use membranes", or
- "a new filtration system for water which removes particle of a certain size that does not use membranes and can be inserted in pipeline".

This variation of context could affect the size of the solution space produced by any of the BID methods and tools. The researcher could not identify any relevant study aiming at assessing such an impact on any BID methodology (where biological information is proposed in different level of detail and organization) and addressing the need of making the methodology more problem-based.
The discussion about "Problem definition" can be therefore connected with the one on "quality/quantity of biological knowledge". How do problem definition and biological knowledge affect each other?

**From the above considerations, it can inferred that the influence on the results of a specific BID method of the type of problem to be solved and its formulation has not been properly researched**

**even if it may play a relevant role in the outcomes of the BID process. In particular, research could be carried out on problem-based BID methods.**

*Costs/benefits of BID*

The cost of the BID process and in particular the cost of the biological search and the organization of the information - which should represent the most expensive part of the BID process – is a crucial variable whose value could influence the effectiveness and future spreading of BID practice beyond the academic environment, into the industrial sector.
The efforts in automatizing the biological search, in literature often considered as "time-consuming" (ex: in (Goel, McAdams, and Stone 2014)) or trying to skip the involvement of biologists (Shu et al. 2011), could be also translated into efforts of cutting the cost for knowledge.
For instance, the Biomimicry 3.8, in its consultancy activity with the industry, tailors its biological search depending on the funding available and delivers to the client up to the description of the biological mechanism. Extracted design principles are discussed with the clients and often left to them to be formulated.
The most successful biological repository for BID activity is AskNature. Its success is due to the large amount of biological solutions organised according to the Biomimicry Taxonomy. The setting up and management of Asknature (which falls under the responsibility of the Biomimicry Institute) is funded by private donors. However, the database is mainly populated via crowdsourcing. Keeping this approach allows to expand the database with many entries at a low-cost, sometimes compromising the quality of the information for each entry; information which is often not enough to extract relevant design principles and requires further investigation to properly understand the biological strategies and mechanisms.
Another source of costs is the learning process to understand and being able to utilize the BID method. Some methods are more intuitive than others. Investing in learning them rather than outsourcing the BID process may not be interesting for industry unless there is a recognized value in those methods and the wish to introduce them systematically in the firm's environment (some staff members of companies such as Interface, Kimberly and Clark, Kohler, Ecover etc. participated to the courses held by Biomimicry 3.8 so as to bring their acquired knowledge within the companies).
Therefore undertaking a BID process has a cost, which needs to be compared with the benefits that this process could generate for different stakeholders having different expectations.

**Based on the above considerations, it is inferred that an analysis of cost/benefits of BID process in both qualitative and quantitative terms has not been carried out yet.**

### 2.3.5 Issues of BID methods and tools addressed by this research

Based on the state-of-the-art reported above, this work aims at addressing the following issues that could increase the effective introduction and utilization of BID in the business sector:

1. BID methods and tools are not yet consistently introduced in industrial environment but remain confined in academic environment. This may reduce the potential for bio-inspired ideas to reach the market.
2. The importance of the quality and quantity of biological information for BID purposes has not been consistently researched, even if it may play a relevant role for the outcomes of the BID process.
3. The influence on the results of a specific BID method of the type of problem to be solved and its formulation has not been properly researched even if it may play a relevant role in the outcomes of the BID process. In particular, there is no evidence of research on problem-based BID methods.
4. Addressing point 2 and 3 above could also provide an indication on Cost/Benefit ration of BID methods; issue which has not been investigated yet. Its estimate would better inform industry about risk/opportunity in embarking in the BID process and selecting the most appropriate BID method.

## 2.4 Research Question

Based on the considerations introduced in this chapter and summarized in section 2.2.6 and 2.3.5, this research wants to contribute to bridge the identified gap between the production of bio-inspired ideas via BID methods and tools and the innovation process brought forward by the business sector. To do this, the following Research Question is formulated:

***How should a BID method/Tool be designed and utilized in order to generate bio-inspired ideas more likely to become innovation in business environment?***

To answer the above broad question, two sub-questions have been formulated:

1. *Which framework of innovation model would enhance the synergy between BID and the Innovation process so as to increase the effectiveness of BID as tool for innovation?*

2. *Which type and amount of biological information should be considered in a BID tool and how to structure it so as to increase the effectiveness of the BID process in terms of ideation metrics? (*this sub-question specifically covers issues raised in section 2.3.2, 2.3.3 and 2.3.4)

As already anticipated in section 1.5, the research will be divided into two main working packages related to the two research sub-questions which will run in parallel (Figure 1-8 reproduced below). Research Sub-question 1, focusing on innovation models, will be answered by a conceptual and qualitative output. Research Sub-questions 2 will be answered by an operative output, a specific BID method, which will undergo a testing and validation procedure. In order to test this BID method the following refined question had to be answered:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

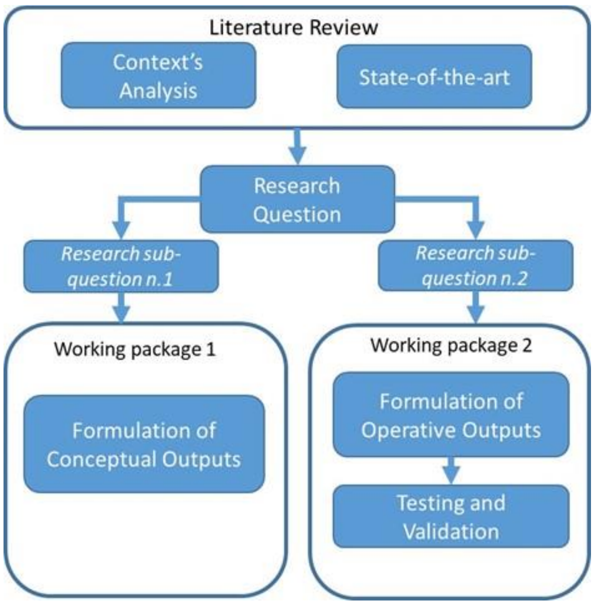



*Figure 1-8: Working packages of the research: Conceptual and Operative outputs*

# 3. RESEARCH STRUCTURE AND METHODOLOGY

## 3.1 Research Structure

The research is developed through sequential steps as per Figure 3-1 and summarized in Table 3-1 below.
Each step was carried out with different approaches, either Qualitative or Quantitative and generated different outputs; either Conceptual or Operative. A map of the overall research structure and methodology followed is provided in Figure 3-7.

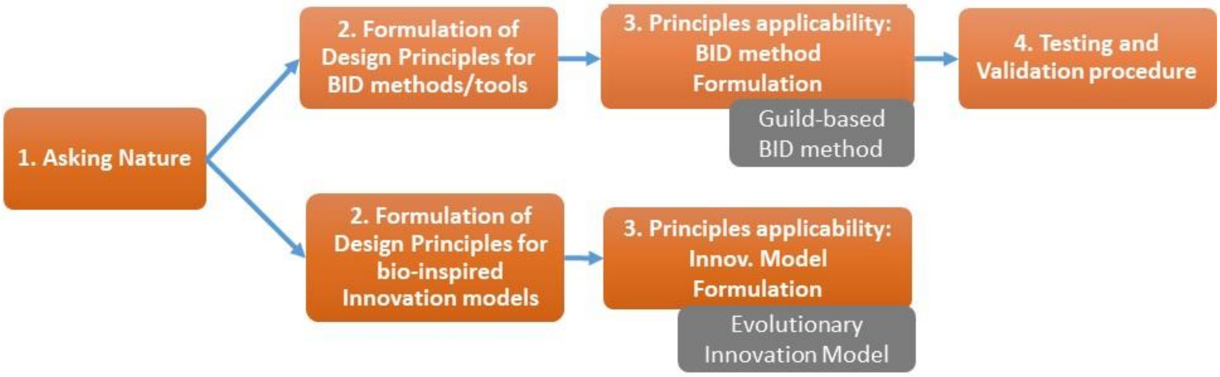



*Figure 3-1: Consecutive Steps (orange boxes) of the research structure. Following a common step of "Asking Nature", the research proceeded in parallel along two paths (two working packages), which generated a conceptual output and an operative output. The latter subject to testing and validation procedure. in grey boxes the two outputs produced (Conceptual one: Evolutionary Innovation Model; and operative one: Guild-based-BID).*

| Step | Brief description | Type of approach/output |
|---|---|---|
| **1. Asking Nature**<br><br>In chapter 4 | This step considers utilizing a BID approach to explore the research question from biological systems perspective aiming at identifying useful biological solutions from which design principles could be extracted to formulate the conceptual outputs of the research sub-question n.1. | Qualitative / Conceptual |
| **2. Formulation of Design Principles for bio-inspired Innovation models**<br><br>In chapter 4 | Based on the biological solutions identified in step 1, design principles are extracted which could assist in designing innovation models more aligned with natural evolutionary processes. The principles find correspondence with existing best practices in innovation management which can enhance the potential of ideation processes (including BID) for generating ideas which will turn into innovation. | Qualitative / Conceptual |
| **2. Formulation of Design Principles for BID methods and tools**<br><br>In chapter 3 and 4 | Based on the key factors (and related considerations) for BID identified in section 2.3.2, a series of *Solving Strategies* are formulated. These strategies, together with some of the principles derived from nature (identified in step 1), are considered as design principles following which it would be possible to design BID methods and tools more compatible with the needs of industrial practitioners. They have been named *BID methods' Design Principles*. | Qualitative / Conceptual |

| Step | Brief description | Type of approach/output |
|---|---|---|
| **3. Principle applicability: Innovation Model formulation**<br>In chapter 5 | The principles for innovation models formulated in step 2, allow answering research sub-question n.1 through their application for formulating a conceptual model for innovation. The model is expected to enhance the effectiveness of the ideation process (including BID) within the business sector. This model has been named *Evolutionary Innovation Model* (EIM) | Qualitative / Conceptual |
| **3. Principle applicability: BID method formulation**<br><br>In chapter 5 | The principles for designing BID methods formulated in step 2 allow answering research sub-question n.2 through their application for formulating a BID method which proposes a specific organization of biological information (in terms of quality and quantity) to increase effectiveness of the BID process. The BID method has been named *Guild-based (*or *Sectoral) BID method (*GB-BID*)*. | Qualitative / Conceptual |
| **4. Testing and Validation procedure**<br><br>**Separation Technology sector**<br><br>In chapter 6, 7 and 8 | The Guild-Base BID method as a potential operative solution to the Research Question (together with the conceptually defined Evolutionary Innovation Model), needs to be tested and validated. To do this, a Refined Research Question needs to be explored:<br>*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*<br><br>In order to reply to this question the following steps have been carried out:<br><br>*1. GB-BID Tool preparation and Innovation Model definition:*<br>Because of the dimension of its market and differentiation of products, the Separation Technology sector was selected in order to test the *Guild-Based BID method* and to provide and conceptual example of *Evolutionary Innovation Model.*<br>The BID tool has been developed via extensive analysis in biology to extract solutions relevant to the main function "to separate". (Chapter 6)<br><br>*2. Testing and Validation:*<br>The BID tool for Separation Technology sector has been tested via ideation workshops and assessment of metrics of effectiveness of the ideation process and production of various case studies. (Chapter 7 and 8) | Quantitative /Operative |

*Table 3-1: Steps of development of the research.*

## 3.2 Research Methodology

Following the research structure, the methodology for each step is presented in the sections below.

### 3.2.1 Asking Nature

The research methodology for this step is conducted through a BID problem-driven approach (as defined in section 2.3.1) until the identification of biological solution. Therefore, the research develops accordingly:

**Problem-driven approach's steps**

**1. Problem definition**

The problem is the research question itself: *How should a BID method/Tool be designed and utilized in order to generate innovative ideas with higher likelihood of becoming innovations on the market?*

- In terms of BID methods and tools, the main and broadest function they have to carry out is to enhance the ideas generation process possibly producing novel ideas.
- The function that an innovation system has to carry out is indeed to innovate and therefore contribute to technology evolution.

Therefore the functional analysis of the research question leads to identify the following functions to be considered:

1. ***To generate novel ideas***
2. ***To Innovate***

**2. Reframe the problem**

Exploring the function "to innovate" in nature seems plausible as "to innovate" and "innovation" are words utilized in biology even if originally taken from technical/industrial domain (Knell and Srholec 2009; Moczek 2008; Moczek et al. 2011). The concept of innovation, in biology, is tightly connected with the one of "novelties" (or new traits/phenotypes) and "evolution". The function "to generate novel ideas" contains an object, "ideas", an abstract concept which is not utilized in biology and therefore needs to be translated into biological terms. However, this translation would result in a complex combination of biological concepts, whose definition is also still open to debate. In order to overcome this difficulty, the researcher proposes to reframe the problem at the broadest possible level of abstraction and focus on the biological function "to evolve". Evolution is the ultimate process to which all biological systems abide and which includes all the possible biological processes that concur in generating potential for novelties, allowing novelties to emerge and allowing them becoming adaptive and being transmissible to future generations.

On this basis of the above considerations, the problem has been reframed in biological terms as:

***How does nature evolve?***

**3. Biological solution search**

The exploration into biology has been carried out through scientific literature available and completed with dialogues with two biologists: one Molecular Biology – PhD - with 5 years of research experience and one Evolutionary Biologist Master Degree with 2 years of experience.

Initial keywords for search in Google and Google Scholar have been combinations of: "biology" "evolution", "innovation", "novelty", "in nature". For instance, *innovation* is a term used also in biology but borrowed indeed from technology/industrial domain. From scientific articles, Wikipedia pages and books related topics, the search led to an exploration which spanned throughout all level of the biological organization (from DNA to Ecosystems). Updated theories and definitions have been explored around concepts such as: Genetic mutation, Horizontal gene transfer, Gene variants,

| |
|---|
| Genotype and Gene Regulatory networks, Epigenetic mechanisms, Exaptation, Evolutionary radiations, Co-evolution, Competition/Mutualisms, Guild-diffuse Co-evolution (more in Chap 4).<br><br>It is relevant to highlight that because of the broad nature of the functions, none of the existing accessible BID related repositories of Biological Knowledge (i.e. AskNature, DANE, Find-Structure) could provide meaningful information as they are focused, largely, on individual organisms and, rarely, on ecosystems rather than on more general biological processes related to evolution.<br><br>A conceptual representation for an ecosystem evolution is proposed by the researcher so as to visualize in an organic way the biological concepts explored (see section 4.2).<br>This one has been further utilized to propose a representation for the concept of Innovation Ecosystems based on System Theory's elements (see section 4.3.6). |
| **4. Definition of the biological solution** |
| Following the investigation of step 3, a series of biological concepts have been proposed as solutions to the initial problem (*How does nature evolve?*) and therefore potentially relevant to be transferred into extracted design principles. These solutions have been selected by the researcher and therefore affected by subjectivity.<br>The biological solutions explored have been categorized according to a biological taxonomy (section 4.3.5). This in order to facilitate the following process of principle extraction and application of the principles at the relevant level of this research. |

*Table 3-2: Steps of the Problem-driven approach followed in the Asking Nature phase of the research.*

### 3.2.2 Formulation of Design Principles for Bio-inspired Innovation Models

From the biological solutions identified in step 1 (Asking Nature), principles have been extracted (section 4.4). The extraction process did not follow any specific existing method/tool if not the indication provided in (Baumeister and et Al. 2011) and (Helms, Vattam, and Goel 2009a) for translating biological solutions into design principles "cleaning" them from biological content.

It is important to specify that in this process of analogical transfer, the researcher tried to disconnect as much as possible from biological physical structures and entities to concentrate on the functionalities of the biological solutions.

The principles extracted could assist in designing innovation models more aligned with natural evolutionary processes.

Also relevant to highlight that the process of transfer identified design principles which find correspondence with existing best practices in innovation management highlighted in the analysis of the context of chapter 2; practices which can enhance the effectiveness of ideation processes (including BID) within and among businesses.

### 3.2.3 Formulation of Design Principles for BID methods and tools

The biological solution identified in step 1 (section 3.2.1) could not be all transferred into specific design principle applicable at the level of BID methods. Only two of them were considered relevant to the process of answering Research Sub-question n.2.

Therefore in order to find a methodological approach to answer that sub-question, the *key factors* and *considerations* related to BID methods identified in the State-of-the-art (section 2.3.2, Table 2-5, Table 2-6 and Table 2-7) have been taken into consideration.

In particular, the *considerations* are positive or negative issues for each key factor identified in reviewed literature. From some of these considerations, the researcher formulated qualitative *Solving Strategies* whose application could enhance positive considerations or neutralize negative ones. One key factor was added by the researcher, named *Problem Contextualization* which relates to the identified need in BID for providing more information on biological solutions' operating conditions

which can make them more transferable as solution to an industrial problem with similar operating conditions and at similar scale, as explained in section 2.3.4.
Below, in Table 3-3, Table 3-4 and Table 3-5, extracted key factors and considerations from section 2.3.2 as well as solving strategies proposed:

*Table 3-3: Key factors in generating ideas and proposed Solving strategies.*

| Key Factors | Considerations | Solving Strategies |
|---|---|---|
| **Modality in Representation** | • Too much superficial detail, which tends to be true of (i.e. detailed prototypes),in representation of analogical stimuli within-domain can have negative effects on design outcomes restricting retrieval of far-field analogies from memory<br>• Some researchers found visual analogies to be most beneficial to design<br>• Others have found that text based stimuli is most beneficial to design.<br>• Still others found that multiple modalities were best for design. | Introduce mixed modalities in representation including visual and textual one. |
| **Expertise**: | • Novices show distinct differences from experts in design-by-analogy execution, and generally have more difficulty with it.<br>• In different and particular domains of knowledge, experts and novices use analogies differently.<br>• Generally, across fields, experts demonstrate behavior that leads to more success in design-by-analogy.<br>• Novices and experts are similar in some respects, including benefiting from visual analogies and susceptibility to fixation, however experts can produce more non-redundant ideas and can mitigate their fixation with the help of defixation materials | Engage experts in the domain of the problem during the ideation process |

*Table 3-4: Key factors in generating bio-inspired ideas and proposed Solving strategies.*

| Key Factors | Considerations | Solving Strategy |
|---|---|---|
| **Cognitive aspects** | • Designers, and novices in particular, have difficulty abstracting strategy level principles during BID, showing particular susceptibility to fixation on superficial details. In particular:<br>○ Students had difficulty in mapping analogies from biology to engineering domain, fixating on applying strategies only to specific parts of the design problem; more generalized descriptions of biological phenomena could help with transfer;<br>○ Designers fixate on irrelevant superficial content of biological knowledge when mapping, and had difficulty identifying the relevant analogy;<br>○ Novice designers tended to map specific features of stimuli, as opposed to identifying an overall analogy and employing it in multiple ways<br>○ Abstraction of biological nouns led novice designers to fixate on other non-abstracted words, e.g., verbs in text descriptions, and reduced ability to understand biological phenomena | Provide both generalized and detailed description of the biological phenomena |
| | • Strategies and recommendations for how to (and how not to) best perform and teach BID have been suggested based on the literature.<br>○ Provide thorough account of cognitive challenges when performing BID, including difficulties with retrieval, inaccurate mental models, improper feature transfer/focus, ignoring of distant analogies, and fixation. Future BID methods/tools should encourage designers to develop multiple concepts based on each biological source, present diverse stimuli with shared underlying principles (multiple analogues), provide uncommon solutions, incorporate structures of categories of the information, and provide abstractions of the biological information. | Present diverse stimuli linked to shared principles (multiple analogues)<br><br>Incorporate structures of categories of information |

| Key Factors | Considerations | Solving Strategy |
|---|---|---|
| **Computational Synthesis/ Automation** | • None of the automated tools suggests solutions to design problems or assess how useful/helpful each piece of biological knowledge might be.<br>• Expandability. The tool should be able to be scaled-up with new biological entries to provide analogies for new specific problems<br>• An automated scalability would reduce costs | Introduce useful/helpful biological information for the problems to be solved<br><br>Be expandable in biological entries for addressing specific problems (Automated or not) |
| **Problem-driven, Solution-driven approach** | • Not all the BID methods and tools facilitate both problem and solution driven approaches | Allow for both problem and solution driven approach |

*Table 3-5: Key factors in bringing bio-inspired ideas to the market and proposed Solving strategies.*

| Key Factors | Considerations | Solving Strategies |
|---|---|---|
| **Awareness and managerial support** | • Participation to the Ideation Phase of firm's managers and other non-technical stakeholders, would increase the chance to move new design concepts through the innovation process. | Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process |
| **Multi-disciplinarity in design team** | • Bio-inspired ideation process in firms is carried out largely without biologists and with teams of maximum two disciplines (ex: engineering and chemistry). This can:<br>- Limit the exploration of biological solution and their understanding with difficulties in transferring to technology (extracting useful design principles).<br>- Prevent addressing the complexity of a problem with consequent generation of solutions which are ill-designed and therefore with less chances to be considered for further development | Provide extracted design principles of biological solutions |
| **Problem Contextualization**<br><br>*Added by the research on the basis of need identified in section 2.3.4* | • Every organism carries out a certain function on a specific object and in a specific context under the influences of biotic and abiotic factors. Similarly innovative products need to operate under specific operating conditions (or fulfil specific requirements) in order to be successful in the market.<br>Biological information on the function's object and its context can therefore enrich the biological analogy in order to make it more transferable as solution to an industrial problem with similar operating conditions and at similar scale.<br>A balance should be reached between a quantity of context narrowing too much the solution space and one opening it too much to miss an optimal solution. Reaching this balance as a cost as retrieving biological contextual information may require more research and cost increase. | Embed biological information of function's object and context which can relate with problem's context and requirements. |
| **Scalability of biological mechanisms** | • Some biological mechanisms work at the nano scale but fail to work on macro scale where their technological applicability would be expected. Example is the gecko attachment mechanism. Synthetic mimics of the gecko's attachment system have failed to show adhesive performance at larger scales. | Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms |

### 3.2.4 Principles applicability: formulation of Innovation Model

Based on the set of design principles extracted mentioned in section 3.2.2, the researcher formulated the framework of a bio-inspired innovation model, named *Evolutionary Innovation Model* (EIM) because of its analogy with evolutionary processes (see section 5.1). Because of the objects of the research sub-question, BID methods and business sector, the entity playing the leading role in the innovation process is hereby considered *the firm*.

The EIM is divided between an internal and external framework:

- The *internal framework* concerns the process of ideas generation which occurs within a single firm;
- The *external framework* concerns the process of ideas generation which involves the firm and other actors external to the firm.

It is important to highlight that the formulation of the model focuses exclusively on the connection between the ideation process and the other innovation phases. It does not expand on other innovation phases and their connections. An expanded framework of the EIM could be possible exploring further biological principles related to evolutionary processes whose abstraction would concern phases such as R&D, Product Development and Commercialization; but it is not the object of this research.

The model proposed represents the answer to Research Sub-question n.1.

### 3.2.5 Principles applicability: BID method's formulation

Based on the solving strategies described in section 3.2.3 an analysis was carried out to determine the level of compliance of the existing and most studied BID methods with the principles.

To the analysis, two additional extracted principles from natural solutions as highlighted in section 3.2.2 were added. These two additional extracted principles were selected as they are related to the ideation process and its actors and they can have an influence on the structure and applicability of BID methods especially in the business sector.

A total of thirteen principles, named *BID methods' Design Principles*, were finally identified:

| | |
|---|---|
| 1. | Allow Building up and replenish a repository of knowledge for Ideas |
| 2. | Useful to specific Business Sectors ("guilds") |
| 3. | Introduce mixed modalities in the representation of the biological solution including visual and textual one |
| 4. | Engage experts in the domain of the problem in the ideation process |
| 5. | Provide both generalized and detailed description of the biological phenomena |
| 6. | Present diverse stimuli linked to shared principles (multiple analogues) |
| 7. | Incorporate structures of categories of information |
| 8. | Be expandable in biological entries for addressing specific problems (automated or not) |
| 9. | Allow for both problem and solution driven approach |
| 10. | Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process |
| 11. | Provide extracted principles of biological solutions |
| 12. | Embed biological information of function's object and context which can relate with problem's context and requirements |
| 13. | Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms |

*Table 3-6: Identified BID methods' Design Principles.*

Following an assessment of the compliance of most researched BID methods and the above principles, based on information available in literature and accessible via the internet, the researcher concluded that none of the existing methods could fulfil all the principles (see section 5.2).

Therefore, with the aim of fulfilling all the principles, the researcher formulated a BID method called *Guild-Based (*or *Sectoral) BID method* (section 5.3.1).

The main feature of this method is to be domain-based or *sectoral* and simplified in its presentation of biological solutions.

The method foresees the creation of biological repositories – databases - for specific functions to be utilized to generate ideas around that specific function.

For every entry (biological solutions), the biological information is distributed across different fields of the database. The database has been encoded in MS Excel, which allows for simplicity in storing information and filtering them.
This organization of biological knowledge in quantity and quality is the proposed reply to the Research Sub-question n.2.

### 3.2.6 What to Test and Validate

The researcher considers the GB-BID method and the formulated principles upon which it has been defined as the main knowledge produced by this research, which should undergo the testing, and validation process.
In this respect, testing and validating the applicability of the GB-BID is considered also an indication of the validity of the principles upon which it has been designed.

*About testing and validate the EIM*

It is reminded that Research Sub-question 1 generated only conceptual answer (the Evolutionary Innovation Model). The initial intention of the researcher was to test the EIM in combination with the GB-BID method. Doing this would have entailed to design the framework of the EIM for a specific business sector, identifying relevant stakeholders of the value chain of the sector and their relationships, and involving them in structured experiments mixed of ideation workshops and production of case studies. This could not been implemented within the frame of this research because of difficulties in involving the business sector up to a statistically meaningful level to draw some conclusions.
However, in order to start pointing in the right direction, the EIM for a specific sector has been developed and related stakeholders participated in one ideation workshop providing some insight for future tests.

## 3.3 Testing and Validation procedure

### 3.3.1 Framing the overall procedure

In order to test and validate the GB-BID method the following refined question had to be answered:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

The procedure has been divided in different steps as per Figure 3-2 below, which are described in detail in the following sections.
In general, the procedure requires the selection of a specific business sector related to a “main function”, its analysis in terms of structure, market, innovation strategy, products and products requirements including current bio-inspired activity (section 3.3.2). Once this information is available, it would be possible to conceptualize an EIM of the sector. In parallel, the GB-BID database on that specific “main function” has to be built up (section 3.3.3).

Two main activities for testing and validation have been carried out: production of *Case Studies* and *Ideation Workshops*.
In particular, these activities have been selected to provide an answer to the refined research question. Affirmative answer to this question would also confirm the GB-BID method as a suitable answer to Research Sub-question n.2 as well as to confirm its utility for the business sector as requested from the main Research Question.

*Ideation Workshops* have been conducted to demonstrate the usability and usefulness of the GB-BID tool when utilized by others. In particular, they have been conducted with different target groups and comparing different format of biological information according to different BID methods. This allows assessing if the GB-BID method:

- Can perform better than other BID methods in generating ideas in the same conditions as other methods. Results in this respect could also allow formulating qualitative consideration around cost/benefit ration of BID. This factor has been already reported as missing from current researches on BID (section 2.3.4), but considered relevant in order to increase effectiveness of BID in the business sector.
  Measuring and comparing metrics of ideation from ideation workshops generated by different BID methods which propose different quality and quantity of biological information (so different costs), could provide insights, even if qualitative, on cost/benefit ration.
- Can perform in multi-target groups environment as well as perform better than other open access BID tools (in particular AskNature);
- Is usable by knowledge-based experts, possibly coming from a sectoral value chain as proposed by the Evolutionary Innovation Model.

The *case studies* aim at providing evidence that with an amount and organization of biological solutions as introduced in a sectoral GB-BID database, several useful outputs can be generated. In particular:

- A sectoral GB-BID database can be consulted to extract overarching (deep) biological solutions to solve the main function of that sector which can set the path for new researches for radically innovative products. (defined as *Sector-level*'s case studies)
- A sectoral GB-BID database can be utilized to support industrial decision-making processes. After having generated a design concept or when a decision should be taken whether to pursuit or abandon certain research paths or business strategies around a product, the GB-BID database could be consulted to assess if, in the natural world, a similar concept/process has been conceived and if yes, under which conditions it operates. This could support the decision making process: "nature did not go that way, why should we?" or "nature did this rather than that, maybe we could try that". (defined as *Sector* and *Sub-sector level*'s case studies)
- A sectoral GB-BID database can be utilized to generate novel ideas for several type of products operating in different contexts but related to the same sector; (defined as *Context-driven level*'s case studies)
- A sectoral GB-BID database can be utilized to generate ideas for product innovation also for sectors not directly related to the main function. (*Across-Sectors level'*s case study)

The GB-BID method was conceived to be compliant with the BID method's Design Principles identified in section 3.2.5. The testing and validation activities selected and carried out allow also verifying this compliance. Below, Table 3-7 highlighting which activity could be accounted as validating the compliance of the GB-BID with each principle.

| BID Method's Design Principle | Activity to verify compliance |
|---|---|
| 1. Allow Building up and replenish a repository of knowledge for Ideas | Set up the GB-BID database for a "main function" |
| 2. Useful to specific Business Sectors ("guilds") | Case Studies and Ideation Workshops for knowledge-based expert |
| 3. Introduce mixed modalities in the representation of the biological solution including visual and textual one | Set up the GB-BID database for a "main function"<br>Ideation Workshops |
| 4. Engage experts in the domain of the problem in the ideation process | Set up the GB-BID database for a "main function" |

| BID Method's Design Principle | Activity to verify compliance |
|---|---|
| 5. Provide both generalized and detailed description of the biological phenomena | Set up the GB-BID database for a "main function" |
| 6. Present diverse stimuli linked to shared principles (multiple analogues) | Set up the GB-BID database for a "main function"<br>Case Studies |
| 7. Incorporate structures of categories of information | Set up the GB-BID database for a "main function" |
| 8. Be expandable in biological entries for addressing specific problems (automated or not) | Set up the GB-BID database for a "main function"<br>Case Studies |
| 9. Allow for both problem and solution driven approach | Ideation Workshops |
| 10. Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process and acknowledging them | Ideation Workshops with mixed target group and knowledge-based experts |
| 11. Provide extracted principles of biological solutions | Set up the GB-BID database for a "main function"<br>Ideation Workshops |
| 12. Embed biological information of function's object and context which can relate with problem's context and requirements | Set up the GB-BID database for Separation<br>Case Studies |
| 13. Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms | Case Studies |

*Table 3-7: Activities of Testing and Validation verifying the compliance of the GB-BID method with the BID methods' Design Principles.*

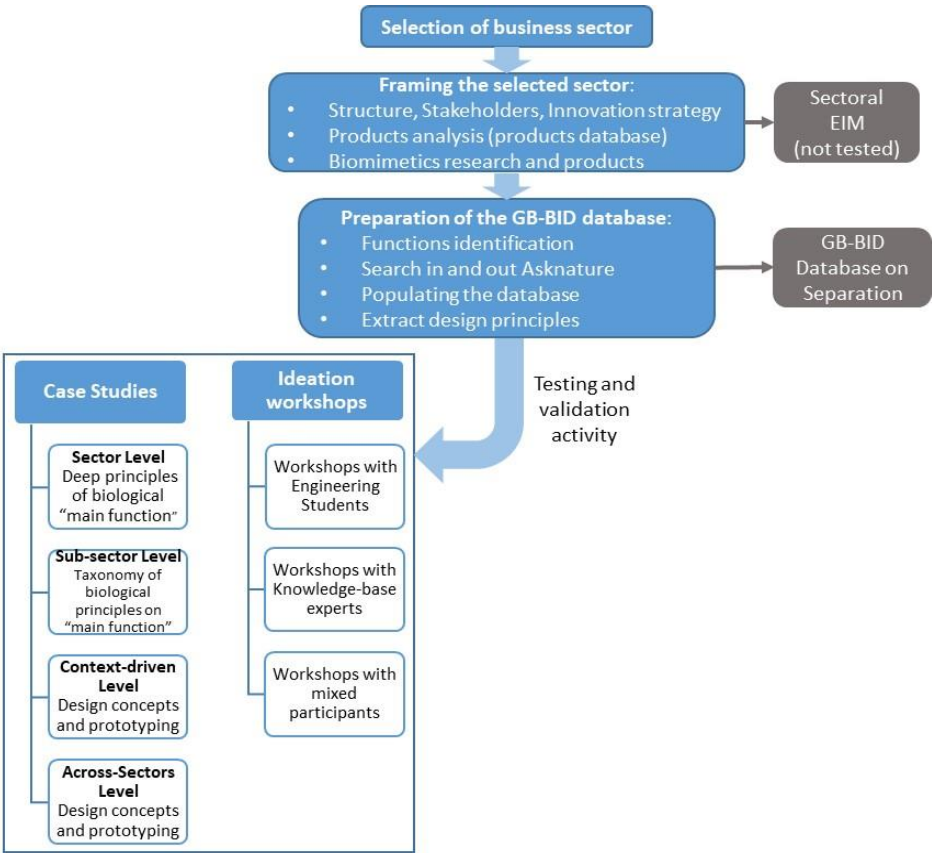



*Figure 3-2: Testing and Validation procedure for the GB-BID Database. The EIM has been conceived for a specific sector but did not go through the testing and validation activity. Blue boxes: specific methodological steps in sequence (connected by light blue thick arrows). Grey boxes: Conceptual and Operative outputs generated. Blue circled boxes: type of Case studies and Workshops carried out.*

### 3.3.2 Framing the target sector - Separation Technology Sector

The first step in the testing procedure is to identify the business sector for which the GB-BID database will be created and therefore the "main function" carried out by products developed in this target sector.
For this research, the sector of Separation Technology was selected because:

- The diversity of products and applications of separation technologies to several other sectors: sectors of water treatment, pharmaceutic, automotive, food sector, chemicals, etc.;
- The size of the market: global business segment approaching $85 billion in annual revenues;
- The complexity of the stakeholders involved and their relationships: suppliers of raw materials for filtering media, filter media makers, filters part makers, filter assemblers and sellers;
- The apparent maturity of many of the technologies for separation. No radical innovation since the last 20-25 years.

Chapter 6 provides a more detailed analysis of aspects of this sector which need to be explored in order to develop the conceptual framework for the Evolutionary Innovation Model and to set up the GB-BID database. In general, for each sector, the following aspects are suggested to be investigated:

- Sector's structure, stakeholders involved (business and customers) and the approach to innovation within the sector; this is relevant to formulate the framework of the EIM;
- Review of exiting products generated by the target sector and preparation of a database of technologies organized according to several fields. The preparation of such a database is not a compulsory procedure, however it helps to identify typical operative factors which are utilized to select a specific product to solve a specific problem. In Engineering Design theory those factors are identified in the "requirements list" step as per (Pahl et al. 2007). These factors are utilized to determine some fields of the GB-BID database such as the ones related to the Main action's Object, Object and Biological mechanism (Process) Conditions and Attributes (section 5.3.1). This allows identifying which biological information need to be introduced in the GB-BID database to be relevant to the sector and allow the users to select relevant biological strategies from which to extract design principles.
  For instance in the case of Separation Technology the following fields where considered: Technology name; Separation principle, Driving force, Type of process, Type of Separation (gas-gas, liquid-solid, etc.). Setting up a database of sectoral's products, even if time consuming, may allow, once the GB-BID database is also available, drawing parallel between technological and biological approaches to solve a recurring problem. It may not help in finding a solution to a specific technical problem, but at least in giving indication about which paths of research may be more promising to follow.
- Assessment of Biomimicry for the Sector: an analysis of existing bio-inspired research and products for the target sector and their success on the market. This type of analysis is relevant to understand the bio-inspired approach of the sector (if any) and which line of products are more subject to bio-inspired innovation and why. This information is useful to shape the content of the GB-BID database in order to adapt it to a recognized trend within the sector and therefore giving the database more chances to be accepted and introduced within the sector.

All the above aspects have been researched through the following approaches:

- Reviewing manuals of products of the sector and deepening specific issues through dedicated scientific literature;
- Google and Google Scholar search combining search keywords such as "biomimetics" AND "*keywords related to processes/products of the sector*" (in this research for instance: "separation", "filtration", etc.);
- Consulting web sites providing statistics on the sector's market and its structure;

- Participating to specialized events of the sector (for instance the researcher participated to a one-day specialized short-course on Separation Technologies at the Filtech Conference-Exposition 2018 (Germany));
- Interviewing companies to understand their approach to innovation and see which innovation model they tend to follow. This has been done within the Filtech Conference-Exposition 2019 (22-24/10/2019 in Cologne -Germany), the largest Exposition in the sector of Separation/Filtration Technology worldwide. As reported in section 6.2.3, representatives of 28 companies (14 from TIER 1 and 14 from TIER 2 level) have been interviewed for 5-10 minutes asking them the following questions:
    - *Is your R&D process internal, external (cooperating with Universities, or companies of the supply chain) or mixed?*
    - *What drives your innovation? Client request of internal pull?*
    - *Do you aim at incremental or radical innovation, or both?*
    - *Do/did you cooperate with competitors? If yes, in which phase of the innovation process?*

### 3.3.3 GB-BID Database preparation – the GB-BID Database for Separation

In this research, MS Excel has been utilized as platform to set up the GB-BID database.
The fields of the Guild-Based BID database for the function “To Separate” have been selected based on the main factors considered when designing separation device for specific purpose (see above section 3.2.6). Once the fields have been identified, the database has been populated with biological entries following the general approach proposed in Figure 3-3 are hereby described for this specific function:

1. Identification of main functions, including synonymous. This has been done into the following steps:
    a. Identification of functions related to “separate” from assessing the specific sector of Separation Technology;
    b. Identification of further functions using the Biomimicry Taxonomy of AskNature;
    c. Subsequent use of these functions as keywords in WORDNET to confirm and find more synonymous;
    d. Review the results from WORDNET removing what is considered not relevant;
    e. Check the results with the Functional Basis to see if something was missing.

    With this approach the researcher believes to have covered all possible synonymous of the function “to separate” which could be use in all domains (Engineering and Biology). A final list of words for functions has been distilled removing figurative meanings of functions (ex: “captivate”, “charm”, “conquer”) and which were considered to be utilized in irrelevant domains to this research (ex: “drum out”, “disgust” “revolt”).
2. With a final list of words for functions, a first search was carried out in AskNature. This produced an initial list of organisms and their biological strategies to carry out that function;
3. For each strategy the biological information were analysed to assess if relevant information were included to populate the various fields of the Guild-base BID database in MS Excel as well as their quality. This activity brought to expand the search into biology outside AskNature.

    The search outside AskNature was conducted starting from the references listed in AskNature and for these references exploring further cited references, which could provide information to fill up all the fields of the database. Following this *cascade* approach in the biological search, not only certain information were retrieved, but also further organisms with different strategies and mechanisms were discovered and start populating the database.

    It has to be noted that for the description of biological strategies and mechanisms, parts of texts extracted form relevant literature were slightly adjusted to be more concise and “to the point”. This exercise was conducted by the researcher and therefore based on his understanding of the information and intention to propose them in the clearest way possible.

4. The population of the database was interrupted at 118 biological solutions considering it a suitable number to conduct some test on the effect of quantity of solutions and produce case studies. The diversity of the organisms selected has not been regulated by any specific procedure however a certain balance has been kept among organisms coming from different kingdoms (animal, plants, fungi, bacteria) and environmental contexts (seawater, forest, desert, etc.). Not all the fields of the database could be filled in with detailed retrieved from literature and a qualitative estimate, based on similar strategies and contexts for which details were available, was made by the researcher. These estimates therefore would need to be further confirmed and/or fine-tuned by domain experts.
5. Once the encoding of the entries terminated, Extracted Design Principles were formulated for more than 90% of the entries. For the missing 10%, the mechanism was considered either too complex or either without detailed information to propose a coherent extraction of principles. The process of extraction was carried out by the researcher himself providing a formulation which removed the biological terms from the biological mechanism, simplify it, but still keep the essence of it. The extraction process has been therefore highly subjective and based on the experience of the researcher. It is however not the scope of this BID method (at least not in the boundary of this research) to provide rigorously proven extracted design principles but to leave room for the users of the BID tool to review and formulate their own.
   This step completed the preparation of the Guild-Base BID database for Separation to be ready for testing and validation.

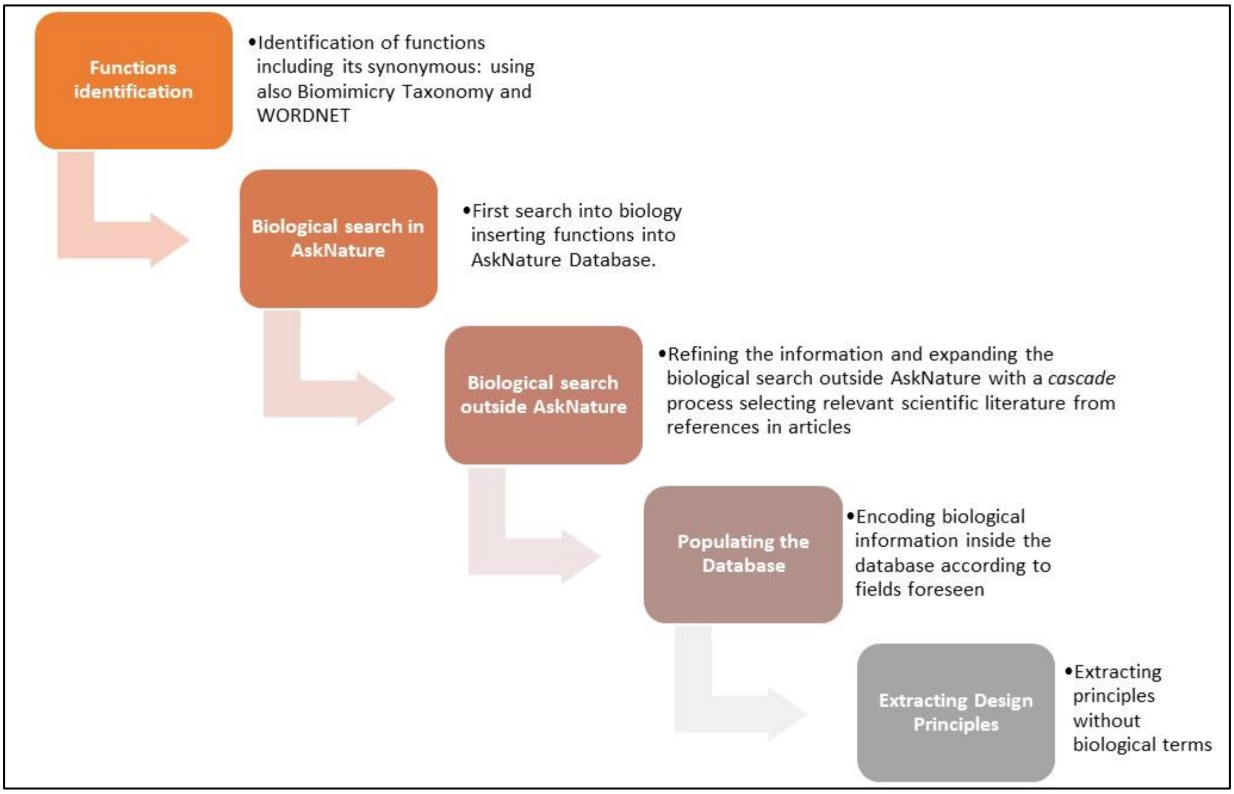



*Figure 3-3: Procedural step in the preparation of the Guild-based BID database.*

### 3.3.4 Generation of Case Studies.

Four types of case studies have been generated consulting the Guild-Based BID database for Separation to address problems/design challenges specific to four different levels of detail:

1. **Sector Level**: problems common to all the types of separation technology; for instance a function such as “to prevent clogging of a filter”;

2. **Sub-sectors Level**: problems specific to sub-sectors of separation technology with functions such as: “to remove particles (or oil) from water” or “to remove particles (or water) from air”;
3. **Context-driven Level**: problems specific to a certain context for which a certain technology is often utilized; for instance: “to desalinate water in arid areas of developing countries”;
4. **Across-Sectors Level**: challenges specific to a different sector than Separation Technology which still requires utilizing the function “to separate”. The sector chosen is the Power Generation sector, sub-sector of High-Voltage Insulators.

The development of case studies selected allows also verifying the compliance of the GB-BD method with some of the BID methods’ Design Principles as per Table 3-6.

The case studies have been mainly developed by the researcher consulting the GB-BID database and utilizing his knowledge about the sector further matured during the period of this research through specialized readings, participation to sectoral conferences and expositions and attending short specialized courses.
For case studies belonging to the levels Context-driven and Across-sectors, the researcher operated within the context of Planet s.a.s, a start-up he co-founded, and through which the opportunities for developing the case studies were generated.
Only in the phase of prototyping, the researcher availed himself sometimes of external expertise to manufacture, assemble and test the prototypes. Details are provided in Chapter 8 for each case study.

It is highlighted the limitation on the scientific validity of the process of generating case studies, which should have been also conducted by third parties independent from the researcher. This could be planned as future research activity.

For each case study, the approach followed has been the classic problem-driven approach of every BID method:
1. Identify a problem to be solved in the Separation Technology sector;
2. Re-formulate the problem in biological term (“How would nature do that?”);
3. Searching in biology querying the Guild-based BID Database for biological solutions;
4. Identify the biological solutions and extract design principles;
5. Apply the principles to generate concepts;
6. Prototyping and testing.

### 3.3.5 Ideation workshops set up

The following types of Ideation Workshops (Table 3-8) have been conceived and carried out:

| Type of workshop | Rationale for target group | Aim |
|---|---|---|
| **Ideation Workshops for mixed-target groups** | These ideation workshops have been carried out to assess the usability of the method with people coming from different background and experience in the logic of a multi-disciplinary ideation process where not only technical but also, let’s say, managerial experts contribute to the creative process. | To assess the performance of the Guild-based BID method in both problem-driven and solution-driven approaches compared to other BID methods such as AskNature, DANE and a version of Guild-based BID prepared by non-expert.<br>This assessment is carried out via main ideation metrics and via questionnaires to participants. |
| **Ideation Workshops for engineering students** | Students of engineering are usually the target group of experiments with BID methods. This because they are supposed to be less biased and less | To assess the performance of the Guild-based BID method in both problem-driven and solution-driven approaches compared to other BID methods such as AskNature, DANE and a version |

| Type of workshop | Rationale for target group | Aim |
|---|---|---|
| | affected by design-fixation than knowledge-based experts when assessing metrics for ideation. Furthermore, workshops with students are also easy to be organized in academic environment and can allow repeatability of the experiments. | of Guild-based BID prepared by non-expert (NE-GBBID). This assessment is carried out via main ideation metrics and via questionnaires to participants. |
| **Ideation Workshops for knowledge-based experts** | Because the target group of the Guild-based BID method is the business sector (in particular industrial practitioners), specific workshops have been developed for this target group. If design-fixation may increase compare to students, also motivation for learning something potentially applicable now in the business may be higher than students. | To assess the performance of the Guild-based BID method in a problem-driven approach compared to AskNature as well as its potential to be utilized in business sector in an Evolutionary Innovation Model framework. This assessment is carried out via questionnaire to participants. |

*Table 3-8: type of ideation workshops held for testing.*

The general set up of the workshop is based on other authors set up for similar testing procedures (Cascini and Becattini 2017; Linsey et al. 2011; Tan et al. 2019).
The workshops for engineering students and mixed-target groups have been conducted following the essential structure of Figure 3-4 but adapted depending on the target group and the specific constraints of time and number of participants.

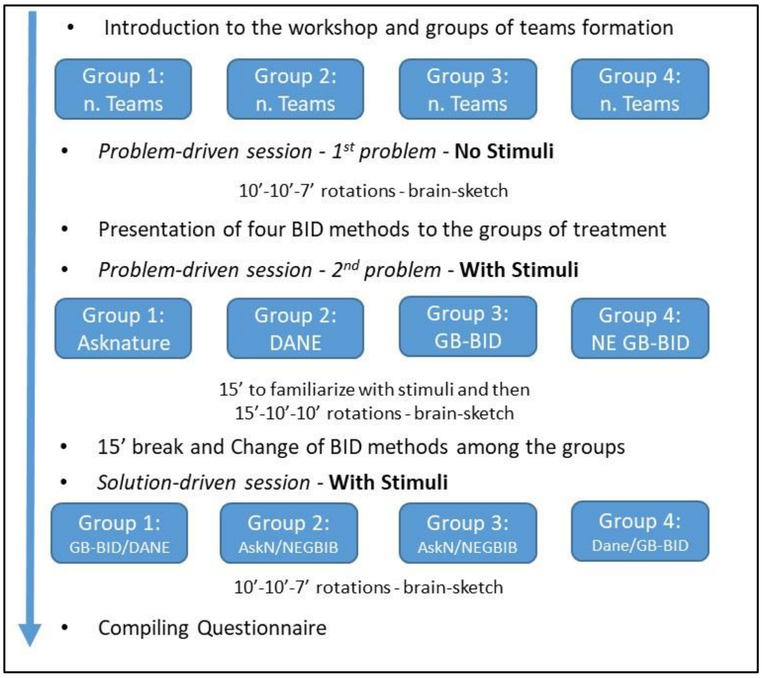



*Figure 3-4: Structure and sequence of activities (listed with bullet points) during Ideation Workshops for mixed target group and engineering students.*

In Table 3-9 below a detailed description of the steps carried out during the workshops:

| Ideation Workshops for engineering students and for mixed-target groups | | |
|---|---|---|
| **Step** | **Description** | **Rational** |
| **Team formation** | Participants are grouped in teams. Random distribution of individuals to form teams of 3 people each. In some workshops, due to the limited number of participants, teams have been formed by two people only.<br>In case the mixed-target groups workshop involved participants with mixed background and different years of experience expertize has been distributed among teams (ex: in one workshop each team had an engineer) | As the sample of the statistical population is represented by "team" there is the need to guarantee a certain uniformity among members of teams so that they can be considered belonging to the same population. |
| **Ideas Representation method and Team work** | Use of ***Brain-sketching*** method where individuals begin by silently sketching their ideas on paper including textual annotations. Then after a certain period of time the papers are exchanged rotating them to the other members of the team. 3 members per team means 2 rounds of exchange. Members can produce new ideas or build up on ideas of the others.<br>Rotation time: 10'-10'-7', 15'-10'-10' depending on the exercise (no stimuli, problem-driven, solution-driven) | The method corresponds to a hybrid 6-3-5/C-sketch method adapted on what proposed by J.L. Linsey at al. (Linsey et al. 2011). It is based on the tested assumption that: if participants generate ideas individually first and then they are exposed to the ideas of other team members, this allows to access associative memory.<br>Participants can:<br>- Use text to describe ideas;<br>- Use sketches. |
| **1st ideation session: Problem-driven - No-Stimuli** | A fist session of ideas generation is held.<br>A problem is proposed: "*How to remove particles from air in the cities*"<br>All teams work on the same problem with no specific stimuli provided.<br>Rule provided: generate as many as possible technical ideas to solve the problem.<br>Rotation time: 10'-10'-7' | The aim is to determine if there is a strong correlation between a team and ideation metrics. If certain teams perform better that other irrespectively of the stimuli.(Cascini and Becattini 2017)<br>To guarantee consistency throughout the overall experiment, the problem provided is of equal complexity of the one provided in the sessions with biological stimuli. |
| **Description of ideas generation methods with biological stimuli from different BID methods** | A 30' slide show presentation to the participants is held by the researcher to introduce BID, explaining Problem/Solution Driven approaches with examples. Furthermore, four different BID methodologies are explained: AskNature, DANE, Guild-based BID prepared by the researcher and Guild-based BID prepared by non-expert* (NE-GBBID).<br><br>The same eight Biological Solutions extracted from the GB-BID database on Separation, but represented into four different formats according to the four BID methodologies, are provided.<br>Distribution of the four formats is done to create four treatment groups including the same number of teams.<br><br>An extra page with a summary list of the eight solutions and their description is provided to all the teams but | The presentation is held following the no-stimuli session in order not to provide the participants with information which they could have utilized already in a no-stimuli session.<br>Participants are however aware of being part of an experiment related to BID methods.<br><br>The biological information have been prepared by the researcher trying to reproduce at his best the original environment of the BID methods (ex: for DANE, the SBF approach as described in the |

| | | |
|---|---|---|
| | the ones with AskNature format. This in order to reproduce as much as possible the quantity and quality of information provided by the different BID methods in their original environment (on-line for DANE and Excel for Guild–Based BID method).<br><br>* the NE-GBBID has been prepared according to the following instruction given to the non-expert:<br><br>*"The scope of this exercise is to fill up the table as much and as detailed as possible utilizing a limited time and information.*<br>*In order to fill up the BIDP Table the following instructions should be followed:*<br><br>*0. each column's title contains a comment to explain the content requested. One row (lotus leaf) has been filled up to provide an example but you can review it and update it according to your findings;*<br>*1. start using the information accessible via the hyperlink connected with the name of the organism (links to AskNature and other websites or downloadable scientific articles);*<br>*2. investigate for further details to fill up the various cells of the table using documents and info freely available in internet;*<br>*3. Complete the table as much as you can (do not worry, some cells might remain empty or the description might be vague) considering a limit of not more than 3-4 hours to be spent for each row (organism);*<br>*4. For each organism list as much as Extracted Design Principles (EDP) you consider appropriate;*<br>*5. Describe the EDP as much as you feel confident that it can be used by technical people to generate ideas for processes and technologies;*<br>*6. You do not have to do everything in one go. Make your research and fill up the table when time suits you.*" | on/line version of DANE was followed including extra information such as photos and short description of the organisms and its strategy.<br><br>For AskNature, visual and textual information have been cut and paste in sheets.<br><br>The NE-GBBID format has been prepared by a graduated management engineer with scarce knowledge about biomimicry and time-bound for filling up each entry (so the detail and quality of information may differ from the tables prepared by the researcher).<br>The use of this format aims at assessing if the quality of biological information within a similar format (the GB-BID database for separation) has an influence on the ideation metrics. Because of:<br>GB-BID=higher quality;<br>NE-GBBID=lower quality;<br>similar values of metrics for both formats could give indication of the decoupling between quality of biological knowledge and performance within the GB-BID method as well as suggesting that cost/benefit ration of GB-BID is not coupled with quality of biological knowledge stored. |
| **2nd ideation session: Problem-Driven with biological stimuli** | The problem for the Problem-Driven session is proposed: "*how to remove humidity from the air in the cities*".<br><ins>Rules provided</ins>:<br>1. Generate as many as possible technical ideas to solve the problem utilizing the biological information provided;<br>2. Solutions should be energy efficient as much as possible;<br>3. Emphasis is not given on the level of detail of the solution. It is left to the participant to decide;<br>4. Indication shall be provided on which biological solution(s) has been emulated to generate each idea.<br><ins>Familiarize with stimuli</ins>: 15' are given to individuals to read and familiarize with the biological information provided.<br><ins>Rotation time</ins>: 15'-10'-10' | The aim is to determine if:<br>• There is a statistically significant difference between the ideation metrics calculated in the no-stimuli and the with biological stimuli session;<br>• There is a statistically significant difference among the ideation metrics calculated for each treatment group. This would indicate different performances among the BID methods utilized.<br>To guarantee consistency throughout the overall experiment, the problem provided is of equal complexity |

| | | |
|---|---|---|
| | | of the one provided in the sessions with biological stimuli. |
| **Break** | At least 15' break between session | Resting time between sessions. |
| **3rd ideation session: Solution-Driven with biological stimuli** | Each team is provided with three biological solutions in two different formats of which one at least new to compared to the ones they had in the problem-driven session.<br>In addition, one of the three solutions is new and not related to the function of the problem-driven session.<br><u>Rule provided</u>: generate as much as possible ideas for solving different problems;<br><u>Rotation time</u>: 10'-10'-7'. | It allows assessing the potentiality of the BID methods for solution-driven approach.<br>It allows individuals to generate ideas not linked to a specific problem and specific domain of knowledge.<br>Each team experiences at least another BID methodology so that qualitative comparisons can be made on the different formats.<br>The introduction of a completely new biological solution for a function different from "to separate" allows testing the BID methods for generating bio-inspired solutions for problems of different sectors. |
| **Questionnaire** | Each participant is requested to fill up a questionnaire (see Annex 4) with questions different aspects of the experience:<br>- Background information (ex: personal data on education and experience);<br>- Opinion of the BID methods utilized;<br>- Opinion on the process (difficulties experienced in different steps, effectiveness of information formats, etc.).<br>A mixed of Likert scales, Yes/No answer and scoring system have been used.<br><u>Duration</u>: 10'-15' | This allows to collect the opinion of the participants around the usability of the BID methodologies utilized and to compare them, highlighting strengths and weaknesses. |

*Table 3-9: Set up and steps of the ideation workshops for mixed background target group and engineering students*

The workshops for knowledge-based experts have been conducted following the essential structure of Figure 3-5 and steps described in Table 3-10.

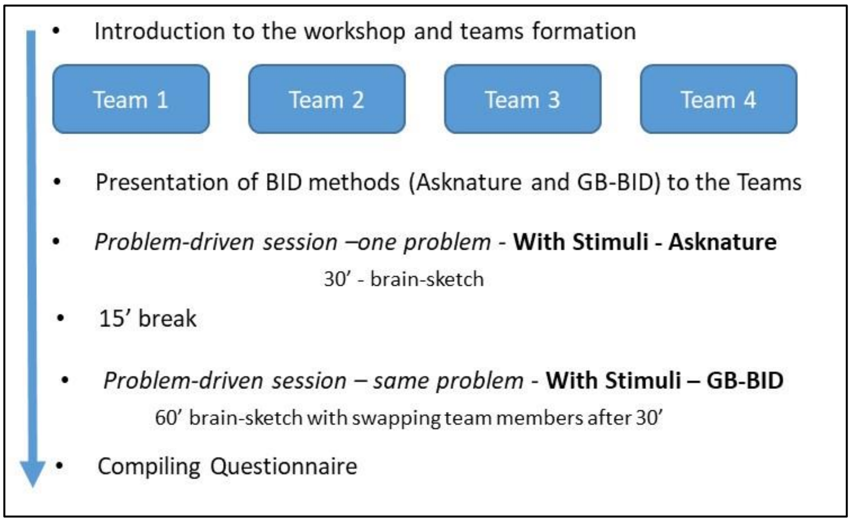



*Figure 3-5: Structure and sequence of activities in the Ideation Workshop with knowledge-based experts.*

| Ideation Workshops for Knowledge-based experts | | |
|---|---|---|
| **Step** | **Description** | **Rational** |
| **Team formation** | Participants coming from different companies are grouped in teams. Random distribution of individuals to form teams of 3 peoples each. | Same rational as per the other workshops. |
| **Ideas Representation method and Team work** | Use of ***Brain-sketching*** method as per previously described workshops.<br>Differently from previous one, team's members:<br>- Can work both individually and in dialogue with other members. No fixed rotation of ideas is expected;<br>- They are asked to swap team in between ideation sessions. | Same rational as per the other workshops but in this case group work is expected without rotation time.<br>Furthermore swapping team members should contribute to increase team's productivity. |
| **Description of ideas generation methods with biological stimuli** | A 45' slide show presentation to the participants is held by the researcher to introduce BID, explaining Problem/Solution Driven approaches with examples.<br>Furthermore, two different BID methodologies are explained: AskNature, and the Guild-based BID. | To provide to the sectoral target group relevant information about BID and its potential for innovation.<br>To provide information on BID methods. |
| **1st ideation session: Problem-Driven with stimuli from AskNature** | The problem for the Problem-Driven session is proposed.<br>Rules for all the teams:<br>1. Consult AskNature on-line to identify relevant biological strategies from which to extract design principles and generate ideas to solve the problem;<br>2. Emphasis is not given on the level of detail of the solution. It is left to the participant to decide;<br>3. Indication shall be provided on which biological strategy(ies) has been emulated to generate each idea.<br>Duration: 30' | To provide participants with a problem which is relevant to their sector and which would motivate them.<br>To learn how to utilize AskNature and generate ideas with its information. |
| **Break** | At least 15' break between session | Resting time between sessions. |
| **2nd ideation session: Problem-Driven with stimuli from Guild-based BID database** | The same problem as per 1st session is addressed.<br><br>Six different biological strategies in GB-BID format as well as the Taxonomy of Biological Strategy for Separation are provided to all the teams.<br><br>Rules for all the teams: same as per previous session;<br>Duration: 60' including familiarization with biological stimuli. | To learn how to utilize the GB-BID method;<br>To assess improvement/differences in ideas generation compared with AskNature. |
| **Questionnaire** | Each participant is requested to fill up a questionnaire with questions different aspects of the experience:<br>- Background information (ex: personal data on education and experience);<br>- Opinion of the BID methods utilized;<br>- Opinion on the process (difficulties experienced in different steps, effectiveness of information formats, etc.)<br>- Information about Ideation process and innovation models applied within the firm<br>A mixed of Likert scales, Yes/No, open answers and scoring system have been used. The questions have been customized on the basis of other similar questionnaires (Baldussu 2014) (Manoj 2016; PwC 2017)<br>Duration: 10'-15' | This allows collecting the opinion of the participants around the usability of the BID methodologies utilized as well as information around their ideation/innovation practice and compatibility with the GB-BID and Evolutionary Innovation Model. |

*Table 3-10: Set up and steps of the ideation workshops for Knowledge-based experts.*

### 3.3.6 Metrics for assessing Ideation process

In order to evaluate the ideas generated during the workshops the following metrics have been utilized: Novelty, Variety, Quantity and Quality (Nelson et al. 2009) (Dinar et al. 2016; 2016) (Oman et al. 2013) (Shah, Smith, and Vargas-Hernandez 2003). Furthermore, additional metrics have been developed because considered relevant for this specific research.

For each metric, some reflections have been made to ascertain their suitability for the purpose and in some cases they have been adjusted. Furthermore specific algorithms for their assessment has been defined which could allow coherence of estimates and calculation among raters and therefore higher chances for repeatability. The table below (Figure 3-6) taken from (Hernandez, Shah, and Smith 2010) lists and describes the original metrics considered. Furthermore,

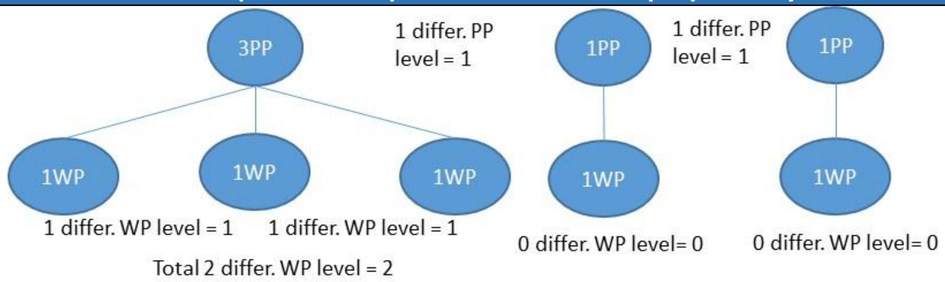
Table 3-11 elaborates on their adaptation for these specific workshops.

| *Effectiveness metrics* | *Calculation* |
|---|---|
| **Quantity**<br>*Definition*: total number of ideas generated. | N |
| **Variety**<br>*Definition*: how different concepts are from each other.<br>*Method*: A group of generated ideas is characterized based on a genealogy-like tree structure that has branches at various levels of physical abstraction: Physical Principle, Working Principle, Embodiment, and Detail. | $M_3 = \sum_{j=1}^{m} f_j \sum_{k=1}^{n} \frac{S_{3jk} b_k}{N}$<br>*where*<br>$M_3$ overall variety score<br>$m$ is the total number of functions<br>$j$ is the function being evaluated<br>$f_j$ is the weight assigned for function $j$<br>$n$ is the number of stages (conceptual, embodiment, etc.)<br>$k$ is the stage in the genealogy tree<br>$S_{3jk}$ is the score given at function $j$ and stage $k$<br>$b_k$ is the number of branches at stage k<br>$N$ is the total number of ideas |
| **Quality**<br>*Definition*: feasibility and conformance to design specifications.<br>*Method*: The score for a given function in an idea is calculated based on answers to a qualitative and quantitative questionnaire. | $M_1 = \sum_{j=1}^{m} f_j \sum_{k=1}^{n} S_{1jk} p_k$<br>*where:*<br>$m$ is the total number of functions<br>$f_j$ is the weight assigned for function $j$<br>$n$ is the number of stages (conceptual, embodiment, etc.)<br>$S_{1jk}$ is the quality score given at function $j$ and stage $k$<br>$p_k$ is the weight assigned to stage k |
| **Novelty**<br>*Definition*: how unusual or unexpected an idea is as compared to other ideas.<br>*Method*: Two approaches can be used.<br>a priori: Before evaluating the ideas, judges predefine known or expected ideas.<br>A-posteriori: Ideas are evaluated based on their occurrences. | $M_1 = \sum_{j=1}^{m} f_j \sum_{k=1}^{n} S_{1jk} p_k$<br>*where*<br>$M_1$ overall variety score<br>$m$ is the total number of functions<br>$j$ is the function being evaluated<br>$f_j$ is the weight assigned for function $j$<br>$n$ is the number of stages (conceptual, embodiment, etc.)<br>$k$ is the stage level<br>$p_k$ is the weight assigned to stage k<br>$S_{1jk}$ is the score given at function $j$ and stage $k$<br>(a priori – based on a table or a posteriori – using the formula to count occurrences:<br>$S_{1jk} = \frac{T_{jk} - C_{jk}}{T_{jk}} \times 10$<br>$T_j$ is the total number of ideas being evaluated<br>$C_j$ is the count of the occurrence of that solution for that function |

*Figure 3-6: Ideation metrics - Extracted from: (Hernandez, Shah, and Smith 2010)*

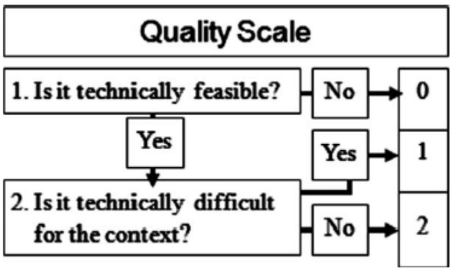
*Table 3-11: Description of ideation metrics and their adaptation for this research*

<table>
<tr><th>Metric</th><th>Description of Adaptation from metrics proposed by Shah</th></tr>
<tr><td>Quantity</td><td>Adaptation from Shah's concept: The workshops measure Quantity only at Concept level which includes Physical Principle (PP) and Working Principle (WP) as per (Peeters 2010) Embodiment stage is not taken into consideration.<br><br>Algorithm for calculation:
<ul>
<li>An idea can be represented by a PP alone (especially in the session with no stimuli) or a PP and a WP
<ul>
<li>PP: this principle is richer than just a Law of Physics but embeds already a law applied to a physical/mechanical/chemical process ex: filtration via mesh, precipitation, coagulation, surface tension (hydrophobicity/philicity)</li>
<li>WP: it is the Physical Principle applied to a mechanism/structure to carry out the function even if structure it is not described in details: Ex: hydrophilic coating applied to building, filtering mesh applied to sewer pipes.</li>
<li>This categorization is considered sufficient to calculate Variety for the purpose of the research.</li>
</ul></li>
<li>If an idea does not address the main function of the problem it shall not be counted.</li>
<li>Ideas can be represented only in written text as long as it is clear at least the physical and, if present, the working principle for application.</li>
<li>Two or more similar ideas in terms of PP <u>AND</u> WP are counted only once (non-repetitive ideas).</li>
<li>If two ideas have same PP but different WP are counted both.</li>
<li>If one idea just completes/enriches a previous one in details, it is counted zero.</li>
<li>if ideas does not apply analogy transfer but bio-utilization (ex: use of organisms instead of emulation of strategy) is counted zero.</li>
<li>If one idea combines more principles (from different organisms) of which only one is similar to another idea, it is counted as 1.</li>
</ul></td></tr>
<tr><td>Variety<br><br>(Nelson et al. 2009)</td><td>Adaptation from Shah's concept: The genealogy-like tree structure has been determined considering the adaptation proposed by Nelson et al. 2009 in order to solve flaws derived from double-counting of ideas and normalization of group score.<br><br>Algorithm:
<ul>
<li>The tree structure foreseen only PP and WP level. Ex: low-drag micro texture (shark's skin like) (PP) applied to pipes in sewer system (WP) or ship's hull (WP) results in score 2 for PP and 1 for each WP.</li>
<li>Assigning points at nodes where differentiation occurs rather than counting the number of branches to resolve the double-counting flaw: "For example, 2 physical principle branches (ndr: into two or more WPs) only corresponds to a single differentiation between physical principles, and 3 physical principle branches corresponds to 2 differentiations, and so on. Thus, the number of differentiations is always one less than the number of branches at a given hierarchical level of a given branch. No differentiations occur when a single branch emanates from a node."</li>
</ul></td></tr>
</table>

| Metric | Description of Adaptation from metrics proposed by Shah |
|---|---|
| | <br>• A non-normalized variety score would measure actual design space exploration, applying to the entire set of ideas rather than averaged per idea. The values of Sk for PP and WP has been therefore set to 10 and 5 respectively so to assures that at least two ideas at the WP level must be added to equal the variety gain by adding a single idea at the PP level.<br>• Therefore the Equation utilized is:<br>$V = \sum_{j-1}^{m} f_j \left( S_1(b_1 - 1) + \sum_{k=2}^{4} S_k \sum_{l=1}^{b_{k-1}} d_l \right)$<br>Where only one key function (the main one related to the problem) considered: fj=1 |
| **Novelty**<br><br>(Peeters 2010) (Srivathsavai et al. 2010) (Shah, Smith, and Vargas-Hernandez 2003) | *Adaptation from Shah's concept:* This metric is used to assess novelty at both concept and feature levels as defined by (Srivathsavai et al. 2010) where a differentiation is made between *basic feature* and *additional features*. Basic features are essential and basically refer to the main functions while additional features are those that are provided by the idea in addition to the basic functions. Following this approach applied to the formulas proposed by Shah et al. 2003, novelty for each idea is calculated as follow:<br><br>***Novelty at Concept level***: calculate according to the formula<br>$M_{concept\ level} = \frac{T-C}{T} * 10$<br>Where T is the total number of ideas produced by a team (the sample population) and C is the count of ideas with the same Physical Principle (but with different Working Principles). In this way, the Working Principle becomes an indicator of novelty.<br>This metric has been applied for the no-stimuli session of the workshop. Because of the lower subjectivity of this approach (no need of defining S1 and expert judgement on these) and because the aim of the session was rather to gather insight regarding the performance of each team inside each group with metrics of process rather than metrics of outcome. Nonetheless, the same metric has been calculated for the sessions with stimuli as a comparison.<br>N.B. As Novelty is scored for each idea, the average of the team is eventually calculated as useful statistical estimator.<br><br>***Novelty at basic and additional features level***: as ideas which did not fulfil the basic feature (read: main function) are rejected (see Quantity), only additional features have been considered. For these the two main approaches have been followed:<br><br>*A-posteriori*: Ideas are evaluated based on their occurrences. For each idea and each stage, an S1 score is calculated according to the number of times this idea, or a very similar one, is proposed and the total number of proposed ideas. If an idea was proposed only rarely by designers, this results in a high S1 score for this idea at that stage. Equation below illustrates this calculation. |

| Metric | Description of Adaptation from metrics proposed by Shah |
|---|---|
| | $$S_{1jk} = \frac{T_{jk} - C_{jk}}{T_{jk}} \times 10.$$ Tjk represents the total number of ideas for function j, while Cjk is the count of the ideas for that function j and stage k (k=1 in this case). The expression is normalised by multiplying by 10.<br><br>*A priori*: Before evaluating the ideas, the rates predefine known or expected ideas. This, following Shah et al. (Shah, Smith, and Vargas-Hernandez 2003) is done by establishing:<br>1. Key Functions and/or attributes which the idea should embed in order to be considered a novelty;<br>2. Weights for each of the above functions/attributes;<br>3. Specific values for S1 which score the degree of unexpectedness or unusualness for each of the functions/attributes.<br>For the latter, the adaptation proposed by Peeters is followed, using S1=10 and 5 also to align with the adaptation proposed in Variety since this assures that at least two ideas must be added at a certain level to equal the novelty gain by adding one idea at a higher level.<br><br>Two attributes have been defined:<br>1. *Energy Source*: in order to assure a certain level of sustainability, the solution to broad problems like the ones addressed in the ideation workshops is required to function with low energy input, possibly adaptable to Renewable energy (RE) sources or even passive. This is considered necessary requirement in developing new technology and because Nature runs on free and renewable energy (Sun, wind, gravity, etc.), it offers solutions which could comply with this attribute. The attribute has been given a weight of 60% and the scores of S1 (10,5,1) are given to solutions presenting specific energy usage set up (passive, using RE or non-RE). To be highlighted that when the description of the solutions was not enough clear to provide a totally unbiased score, the subjectivity of the raters (who have nonetheless some years of experience in energy systems) prevail in the scoring.<br>2. *Adaptability*: also for this attribute, in order to assure a certain level of sustainability, solutions are assessed according to their impact on the built environment (and consequently also a certain correlation with the costs for implementing them). The attribute has been given a weight of 40% and the scores of S1 (10,5,1) are given to solutions being able or not to be integrated with the built environment (retrofitting the existing environment, in need of a dedicated structure or in need to radically modify the existing built environment). To be highlighted that the description of the solutions was in general enough clear to provide an unbiased score by the raters. |

| | | **Novelty score a Priori** | | |
|---|---|---|---|---|
| **Key functions/ attributes** | **Weight** | **S1=10** | **S1=5** | **S1=1** |
| F1 - Energy source | **0.6** | 100% Passive solution | Active process with indication of use of RE | Active process using non RE |
| F2 - Adaptability | **0.4** | retrofitting the existing | dedicated structure | change of existing built environment |

| Metric | Description of Adaptation from metrics proposed by Shah |
|---|---|
| **Quality**<br><br>(Shah, Smith, and Vargas-Hernandez 2003) | *Definition*: feasibility and conformance to design problem. It estimates the likelihood of successfully designing and manufacturing the product. The quality scale proposed by Shah et al. has been utilized however with some specific adaptations:<br><br><br>*From* (Shah, Smith, and Vargas-Hernandez 2003)<br><br>*Method:* scoring system where Quality=score<br>*Algorithm for scoring:*<br>• Score 0 if solution is against the law of physics;<br>• Score 0 to ideas which could be realistic and potentially feasible but R&D needed is considered extensive and complex;<br>• Score 0 if Physical principle is mentioned but no clear working principle is described to assess its feasibility;<br>• Score 0 when applicability to the problem is not clear but only the PP and WP are mentioned;<br>• Score 1 if technology (materials and processes) is judged to be already existing but need to be improved/scaled up and adapted via R&D;<br>• Score 2 if technology is judged to be already available in terms of materials and production processes, scalability feasible but combination was not attempted yet (not complex R&D needed).<br><br>N.B. As quality is scored for each idea, the average of the Team is calculated as useful statistical estimator. |
| **Novelty/ Quality Percentage and Maximum values**<br><br>(Jia et al. 2020) | For what concerns Novelty and Quality, whose assessment regards single ideas, additional statistical estimators have been calculated such as:<br><br>**Percentage Novelty (Quality):** each idea gets its score. The percentage is calculated as the ratio between the ideas whose score overcomes a given threshold value (decided at 0.70 for Novelty and 1 for Quality) and the overall amount of generated ideas.<br><br>**Maximum value for Novelty (Quality):** each idea gets its score. The maximum value for each team is computed by adding the scores of the N top-rated ideas. The choice of N depends on the minimum quantity recorded among the teams. In the test it was selected N=3. |
| **Originality**<br><br>(Srivathsavai et al. 2010) | *Definition*: Trivial/Non-Trivial Bio-inspired idea. The originality metric is a subjective measurement of how innovative the evaluator finds the bio-inspired idea. It does rely on the evaluator's knowledge of the marketplace and existing scientific research related to the idea to be assessed.<br>*Method*: scoring system where Originality=Score<br><br>*Justification*: this metric is utilized to provide further judgement on Novelty of the ideas. As key functions and attributes in Novelty metric refers more to technical features of the ideas. Originality is utilized in this context to evaluate, based on the description and details |

<table>
<tr><th>Metric</th><th>Description of Adaptation from metrics proposed by Shah</th></tr>
<tr><td></td><td>
provided by the designer the degree of originality indeed in the context of bio-inspired solutions. It is therefore a metric of outcome. Raters for this metric should be experts in bio-inspired solutions having a knowledge about a wide spectrum of existing (at idea, R&D or market level) biomimetic solutions related to the addressed initial problem.<br>
Furthermore, Originality differs from another metric proposed, “Bio-emulation”, which is considered a metric of process rather than outcome.<br>
The following coarse granularity and scoring is proposed based on the initial point-scale proposed by Srivathsavai et al. 2010 adapted from (Charyton, C., Jagacinski, R. J., & Merill J. A., 2008)<br>
This metric, together with Bio-Emulation one, wants also to highlight the effort of the designer in conceiving and describing his/her ideas. Conscious of the fact that time for generating ideas is limited (10 min each round), designer who puts more effort in describing their ideas gets a higher score.<br><br>
Algorithm for scoring:
<table>
<tr><th>Attribute</th><th>Score</th><th>description</th><th>Ex:</th></tr>
<tr><td>Common</td><td>0</td><td>Bio-inspiration already largely known and superficially described</td><td>Submarine covered with shark’s skin-like textured surface to improve hydrodynamics</td></tr>
<tr><td>Uncommon</td><td>3</td><td>Bio-inspiration un-common but solution is trivial/known and not elaborated</td><td>Façade of buildings painted with super-hydrophobic paint mimicking lotus leaf’s effect</td></tr>
<tr><td>Interesting</td><td>7</td><td>Bio-inspiration mentioned and non-trivial/known solution</td><td>shark’s skin-like textured applied in filtering devices to produce super-oleophobic behavior in water</td></tr>
<tr><td>Exceptional</td><td>10</td><td>Bio-inspiration un-common or non-obvious abstraction of biological solution and non-trivial solution</td><td>N.A. to be decided by the rater</td></tr>
</table>
</td></tr>
<tr><td>Bio-Emulation<br><br>Defined by the researcher</td><td>
Definition: it scores the quality/degree of the transfer of the biological analogy of a single idea based on the information provided by the ideator.<br>
Method: scoring system where BE=Score<br>
Justification: this metric is utilized to provide judgement on the biological analogy transfer process. The transfer can be influenced by several factors, amount and quality of biological information provided, understanding of the process by the ideator (this however could be also affected by how the task is correctly introduced by the experimenter), his/her capacity to extract design principles as well as time constraint given to the ideation process. The metric has to be assessed by experts in BID methods and can provide evidence of the effectiveness of a BID method compared to another.<br><br>
Algorithm for scoring:
<table>
<tr><th>Score</th><th>Description</th><th>Ex:</th></tr>
<tr><td>1</td><td>No Extracted Design Prin. - Only mentioned organism's biological strategy</td><td>Façade of a building which is super-hydrophobic by mimicking the surface of a lotus leaf</td></tr>
</table>
</td></tr>
</table>

| Metric | Description of Adaptation from metrics proposed by Shah | | | |
|---|---|---|---|---|
| | 5 | Strategy/mechanisms mentioned in non-biology terms and applied though not precisely | Façade of a building covered with nano-textured surface providing super-hydrophobic property | |
| | 10 | Evidence of Extracted Design Principle applied (identifiable in text and drawings)/richness of details | Façade of a building covered with a nano-texture coating where nano-bumps have x-height, y-diameter and d-density. The texture generate super-hydrophobic behavior | |

*Metrics calculations and Validation*

In order to calculate the metrics as well as test the repeatability of the experiment, the ideas generated during the workshops have been assessed by 2 raters experts in the sectors of Biomimicry as well as Separation Technologies: one is the researcher and one is a junior engineer designer with 4 years of experience in bio-inspired innovation in the separation technology sector (and Master thesis on bio-inspired oil-water separation).

The procedure to evaluate the sets of ideas has been discussed beforehand in order to create common understanding. Furthermore, around 10% of the ideas generated in both rounds (the ones with and without stimuli) have been evaluated by both raters together. Then the evaluation proceeded separately. Data have been recorded in MS Excel environment.

Because of the uncertainty around the normality of the distribution of the dependent variable and there might not be approximately equal variance on the scores across the groups under test non-parametric tests have been conducted on the dependent variable (the metrics). In particular, the non-parametric tests have been utilized (Table 3-12) which are usually utilized in assessing ideation processes:

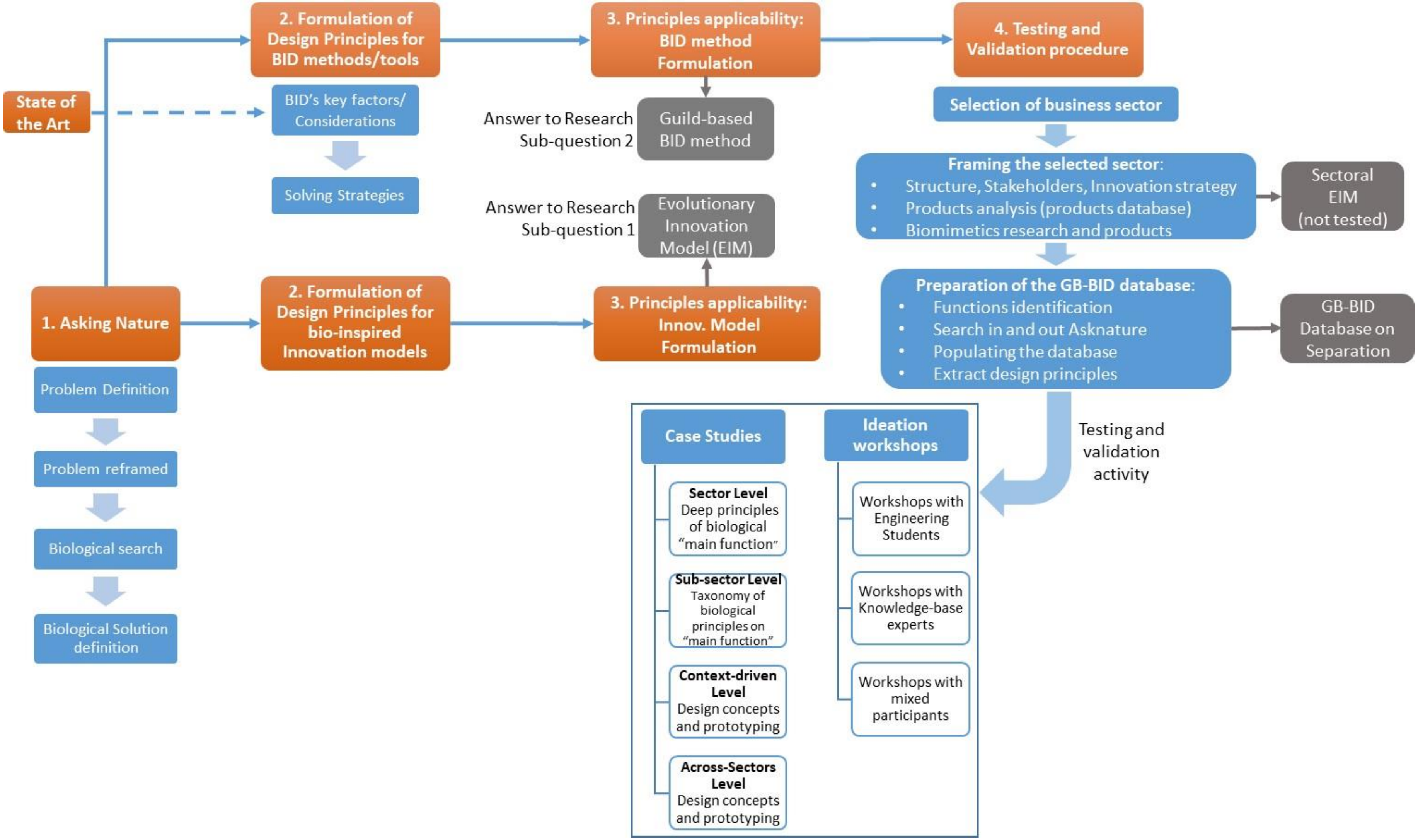
*Table 3-12: Non-parametric tests utilized to test correlation among raters and among teams in treatment groups.*

| Type of test and use | Description |
|---|---|
| **Mann-Whitney**<br><br>To test correlation among raters | Non-parametric test of the null hypothesis that it is equally likely that a randomly selected value from one population will be less than or greater than a randomly selected value from a second population. This test can be used to investigate whether two independent samples were selected from populations having the same distribution. (the nonparametric counterpart of an independent measures t-test).<br>This test works on ranking the data rather than testing the actual scores (values), and scoring each rank ignoring the group to which each participant belonged. The principle of the test is that if the groups were equal (coming from the same population), then the sum of the ranks should also be the same.<br>The test involves the calculation of a statistic, usually called U, whose distribution under the null hypothesis is known. U can be calculated with the following formula:<br>$\mathbf{U} = n1 \times n2 + nx \times \frac{(nx+1)}{2} - Tx$<br>Where *n1*, *n2* and *nx* are the number of participants in each group, and the number of people in the group that gave the larger rank total. Tx is the larger rank total.<br>Once U is calculated then the critical U values are selected in the table for the Mann-Whitney U Test for 5% and 1% significance.<br>The method does not need corrections for ties. |

| Type of test and use | Description |
|---|---|
| **Kendall W**<br><br>To test correlation among raters | Assume there are *m* raters rating *k* subjects in rank order from 1 to *k*. Let $r_{ij}$ = the rating rater *j* gives to subject *i*. For each subject *i*, let $R_i = \sum_{j=1}^{m} r_{ij}$. let R$\bar{R}$ be the mean of the $R_i$ and let *R* be the squared deviation, i.e.:<br>$R = \sum_{i=1}^{k} (R_i - \bar{R})^2$<br>Kendall's *W* is defined by:<br>$W = \frac{12R}{m^2(k^3 - k)}$<br><br>When there are a lot of ties, the following revised definition of *W* can be used.<br>For each rater *j*, define<br>$T_j = \sum_g (t_g^3 - t_g) \qquad T = \sum_{j=1}^{m} T_j$<br>where the *g* are all the groups of tied ranks for rater *j* and $t_g$ = the number of tied ranks. Now define *W* as follows.<br><br>$W = \frac{12S^2 - 3m^2k(k+1)^2}{m^2(k^3 - k) - mT}$<br>It is always the case that $0 \le W \le 1$. If $W = 0$ then there is no agreement among the raters. |
| **Kruskal-Wallis**<br><br>To test correlation among teams | The Kruskal-Wallis test can be used for both continuous and ordinal-level dependent variables.<br>*Step 1*: Sort the data for all groups/samples into ascending order in one combined set.<br>*Step 2*: Assign ranks to the sorted data points. Give tied values the average rank.<br>*Step3*: Add up the different ranks for each group/sample.<br>*Step4:* Calculate the H statistic:<br>$H = \left[ \frac{12}{n(n+1)} \sum_{j=1}^{c} \frac{T_j^2}{n_j} \right] - 3(n+1)$<br><br>Where:<br>• n = sum of sample sizes for all samples,<br>• c = number of samples,<br>• $T_j$ = sum of ranks in the $j^{th}$ sample,<br>• $n_j$ = size of the $j^{th}$ sample.<br>*Step 5:* Find the critical chi-square value, with c-1 degrees of freedom. In our case for 4 – 1 degrees of freedom and X2 at 5%.<br>*Step 6:* Compare the H value from Step 4 to the critical chi-square value from Step 5.<br>If the critical chi-square value is less than the H statistic, reject the null hypothesis that the medians are equal.<br>If the chi-square value is not less than the H statistic, there is not enough evidence to suggest that the medians are unequal. |

Metrics values have been encoded in MS Excel and tests have been conducted in MS Excel environment.

*Figure 3-7: Overall Map of the Research: Orange boxes: phases of the research in sequence (connected by blue thin arrows). Two working packages running in parallel (phase 2 and 3 for each package and phase 4 for one package only). Blue boxes: specific methodological steps in sequence (connected by light blue thick arrows) within related research phase. Grey boxes: Conceptual and Operative outputs generated (grey arrow). Blue circled boxes: type of Case studies and Workshops carried out. To be noticed results coming from the State-of-the-Art informing phase 2 (blue dashed line)*



# PART 2

# INVESTIGATION AND PROPOSALS

# 4. ASKING NATURE

As described in Chapter 3 section 3.2.1, the research methodology for this step is conducted through a problem-driven BID approach until the extraction of design principles from Nature. Therefore, the research develops as follows:


*Figure 4-1: Steps of the BID approach conducted in sequence.*

## 4.1 Problem definition/analysis and problem reframed

Recalling the research question (the *problem*):

*How should a BID method/Tool be designed and utilized in order to generate bio-inspired ideas more likely to become innovation in business environment?*

- In terms of BID methods and tools, the main and broadest function they have to carry out is to enhance the ideas generation process possibly producing novel ideas.
- The function that an innovation system has to carry out is indeed to innovate and therefore contribute to technology evolution.

Therefore, the functional analysis of the research question leads to identify the following functions to be considered:

- ***To generate novel ideas***
- ***To Innovate***

Considering the difficulties in translating the functions "to generate novel ideas" and "to innovate" across the two domains (from technology to biology), as explained in section 3.2.1, the problem was reframed in biological terms from a broader perspective:

***How does nature evolve?***

## 4.2 Biological search and Biological solution definition

Answering to the above question means exploring the process of natural evolution. The topic is vast and encompasses several sub-domains of biology.

The research into biology has been carried out via a cascade process of consultation of sources of biological knowledge as follow:

1. Life Science Text Books;
2. Books on Evolutionary processes;
3. Search in Google and Google Scholar with combination of the following keywords: "*biology*" "*evolution*", "*innovation*", "*novelty*", "*nature*". To be noticed that the term *innovation* is a term used also in biology but borrowed indeed from technology/industrial domain;
4. Wikipedia pages of available key biological concepts;
5. Expansion of investigation through review of scientific literature from specialized journals and referenced papers.

For some of the biological concepts identified, a further clarification has been sought discussing with two biologists.

### Note on lack of globally accepted meaning of some biological concepts

One important aspect to be mentioned is that biological knowledge seems lacking of standardized definition of certain concepts commonly accepted by the relevant scientific community and utilized in scientific literature. For instance the term “species”, a key concept in biology, seems having more than 30 different interpretation (Douglas 2019) . “Ecological niche” has also at least three different interpretations (Polechová and Storch 2008), as well as “adaptation” (Wikipedia) and evolutionary “novelty”(Peterson and Müller 2016).
Some biological concepts described in Life Science Text Books are in fact still open to debate and interpreted differently by different research groups and under different theoretical frameworks (Darwinian, Evo-Devo). Some concepts are in constant evolution as new theories are coming along (such as Extended Evolutionary Synthesis and Evo-Devo) and some paradigms are shifting.
All this, especially when applying BID at system level, may generate inaccurate principle extraction depending on the source of the biological knowledge, or at least extraction of principles which may be deemed to evolve as biological concepts evolve.
Therefore, the principles extracted in this research are based on updated meanings of concepts and in case ambiguity of meaning exists, it is reported.

As concepts such as evolution, novelty and innovation span across all the biological organization (from DNA to Ecosystem level), it has been considered important to organize the information and structure them in a way which could facilitate non-biologists in understanding them, locating them in the right context and utilizing them for further research in BID context.

Therefore, the concepts explored have been organized according to the following nested structure of domains of knowledge (Table 4-1):

*Table 4-1: Organization of biological concepts explored according to a nested structure*

| Levels | **Description** (from Wikipedia) |
|---|---|
| **Genomics and Epi-genomics** | Genomics is an interdisciplinary field of biology focusing on the structure, function, evolution, mapping, and editing of genomes. A genome is an organism's complete set of DNA, including all of its genes. In contrast to genetics, which refers to the study of individual genes and their roles in inheritance, genomics aims at the collective characterization and quantification of all of an organism's genes, their interrelations and influence on the organism.<br>Epigenomics is the study of the complete set of epigenetic modifications on the genetic material of a cell, known as the epigenome. The field is analogous to genomics. |
| **Phenomics and Development** | Phenomics is the systematic study of phenotypes/traits (expressed genes). It is concerned with the measurement of phenomes where a phenome is the set of phenotypes (physical and biochemical traits) that can be produced by a given organism over the course of development and in response to genetic mutation and environmental influences. |
| **Ecology** | Ecology studies the interactions among organisms and their biophysical environment, which includes both biotic and abiotic components. |
| **Environment** | In the context of this research, Environment it is described as the combination of external abiotic factors which can affect evolution from outside the organisms. |

Below, in Figure 4-2, a representation of the nested structure and the concepts explored which are affecting the evolutionary process at different level of the biological organization (from DNA to Populations) and which belong to the different sub-domains of biological knowledge:

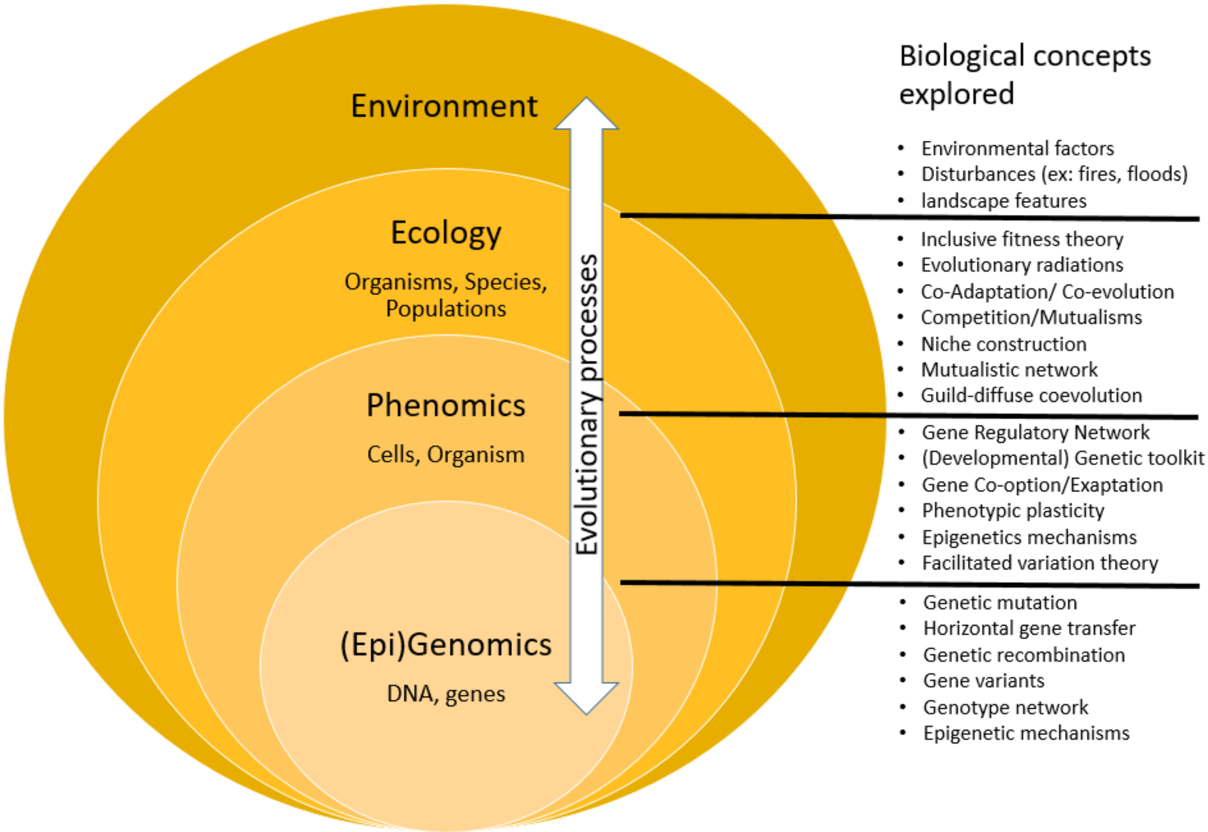



*Figure 4-2: Representation of the nested structure of biological concepts explored. Each circle represents the level of the biological organization when certain concepts are encountered. The various biological concepts have been clustered to specific levels through often they can operate across levels. The evolutionary process occurs across the circles in both directions.*

## 4.3 Biological Solutions

All the above concepts explored and their description are reported as Annex 2. Despite all these concepts could be utilized as analogy and design principles could be extracted and used in BID processes for different purposes, a deeper analysis has been carried out only of those biological concepts, which have been considered more relevant for this research.
For each sub-domain of biological knowledge, the list of concepts explored is sometimes enriched with basic definitions which allow better understanding the concepts.
In the following sections an attempt was made to connect the separate concepts in a more fluid description of the process of evolution (from an internal and external perspective on an organism) which ultimately leads to identification of natural principles to be extracted (section 4.3.6).

### 4.3.1 From Epi(genomics) to Phenomics

The first and main potential for generation of novelties and therefore for evolution, lays at genetic level and it is represented by the pool of genes variations. The more genes can vary and variations are stored in the genotype, the wider the solution space, the more and diverse traits (phenotypes generated through gene expression) can potentially emerge. A *novelty* is therefore a new trait (phenotype) which can be either a new morphological structure (or a similar one but in a different part of the organism's body), a different internal process or even a different external behaviour. Novelty can therefore be present at and have an effect on different levels. It can affect the gene regulatory network as well as the genetic toolkit, those internal processes which regulate genes expression and the development of the organism from its embryonic to mature state.

Variations of genes can be produced by different mechanisms, internal to the process of development and growth of a single organism: such as random mutations, exchange of genetic material among cells, errors during replications of cells as well as duplications (genetic redundancy). All these processes contributed to increase the pool of genes available, the breath of the solution space, which does not necessary end up to be expressed in traits (phenotypes) but they will be transmitted to further generation of organisms ready to become new traits (novelty) when necessary conditions for them to be expressed will occur.
So-called *Epigenetic mechanisms* can trigger genes expression mechanisms to generate new traits without *involving alterations in the DNA sequence* (they operate with the pool of gene variants without creating new ones). Epigenetics mechanisms are triggered from external conditions such as changes in environmental and ecological factors. An epigenetically-modified trait can arise simultaneously in many individuals, as opposed to a single individual with a gene mutation. The new traits emerging however can be temporary and disappear throughout generations.

Novelties, new traits, can be generated also by *co-opting* existing genes where co-option (or *Exaptation*) occurs when natural selection finds new uses (functionality) for <u>existing</u> traits (this includes genes, organs, and other body structures and behaviours). Genes can be *co-opted* to generate developmental and physiological novelties by changing their patterns of regulation, by changing the functions of the proteins they encode, or both.
However, co-option does not necessarily imply novelty, but rather new functionality using what is already existing (Birds feathers are a classic example: initially they may have evolved for temperature regulation, but later were adapted for flight), and novelty does not necessary imply new functionality. Indeed a novelty could rarely generate a new functionality by itself (ex: wings popping out from body part in a single generation), but rather progressively (through generations) it promotes the appearance of new functionalities or reinforces the success of others already existing (ex: a six finger hands could allow new functionalities as well as increasing the functionality of grabbing objects).

It should be emphasised that novelty at one level (e.g., a new gene) should not be used to determine novelty at another level (e.g., a new morphological structure). This is due to the loose causal connections between levels of the biological organization. As new combinations of existing genes can produce threshold effects, novel structures may appear without the introduction of novel genes. Similarly, the introduction of a novel gene does not guarantee a novel tissue or morphological structure.

### 4.3.2 From Phenomics to Ecology

When a gene variant succeeds in being expressed, becoming a new trait of a single organism, or a novelty, this is enough for this trait to be called, in biology terms, an *innovation*, however not enough to be branded as an "evolutionary" novelty/innovation. In order to become as such, according to Pigliucci (Pigliucci, Müller, and Konrad Lorenz, 2010), the new trait should be coupled with a new functionality within the ecology of that specific species. We can talk therefore about evolutionary innovation when the new trait:

1. It is transmitted to future generation (it is therefore *adapted*).
2. It can be an absolute discontinuity but more often built on previously existing traits (co-opted).
3. It requires some kind of ecological functionality.

Furthermore, it is not necessary that the new trait provides a new functionality to the organism but it has to contribute to increase its fitness within the ecosystem.

Therefore *Evolutionary novelties are new traits or behaviours, or novel combinations of previously existing traits or behaviours, arising during the evolution of a lineage, and that perform a new function within the ecology of that lineage.*
The processes generating phenotypic novelty are separated from the ecological and evolutionary processes that regulate their success. Indeed in some cases the molecular and developmental origin of new phenotypic characters may often be independent of ecological opportunities, with novelty arising long before a species diversify (adaptive radiation) declaring the success of the new trait.

**Evolvability** is the ability of a population of organisms to not merely generate genetic diversity, but to generate *adaptive* genetic diversity, and thereby evolve through natural selection. A. Wagner (Wagner 2014) proposes two definitions of evolvability:

1. A living system is evolvable if its properties show heritable genetic variation, and if natural selection can thus change these properties.
2. A living system is evolvable if it can acquire novel functions through genetic change, functions that help the organism survive and reproduce.

### 4.3.3 External factors affecting the evolutionary process

As already highlighted, novelties are represented by new traits which can emerge through a continuous (quantitatively identifiable through several generations) or discontinuous (qualitatively identifiable in one generation) process, either via expression of gene variants, via modification of the gene expression/developmental processes (via epigenetic mechanisms) or via recombination of existing traits (co-option).
New traits can bring new functionalities or not, they can be temporary (so their inheritability and then adaptability can terminate) or lasting, they can trigger the emergence of new species or not (in the former case we talk about adaptive radiation/speciation).
The various processes triggering novelties emergence within an organism descripted above can be influenced by various external factors. Factors which therefore participate to the overall process of evolution. These factors can be *abiotic*, so changes in a, so far stable, environmental landscape (for instance change in climate, morphological landscape, changes in access to resources) or *biotic*, so changes induced by indirect or direct action of other organisms. Both abiotic and biotic factors concur therefore in changing the pre-existing state of the *ecological niche* occupied by a certain organism triggering the activation of its evolutionary mechanisms. The ecological niche describes *both the range of conditions necessary for persistence of the species and its ecological role in the ecosystem.* From the perspective of the species "A" whose niche was perturbed, there are the following possibilities:

1. To move to another niche where resources are available, and in doing so, contributing to disturb other species belonging to the new niche which were covering the same functional role of the new comer;
2. To adapt and co-exist with the abiotic and biotic (ex: competitors) factors through a *niche differentiation/partitioning* of to use the resources differently (ex: an advantage of *generalists* species which can accept food from different sources compared to *specialist* species that can only feed on one type of food);
3. To construct a new niche, where '*niche construction*' refers to the process whereby the metabolism, activities and choices of organisms modify or stabilize environmental states, and thereby affect natural selection acting on themselves and other species;
4. In case the perturbation was generated by the evolution of a species "B" within the niche, and this species is directly or indirectly connected to the species "A", this last one can *co-evolve* and/or *co-adapt* to the evolved species "B". In co-evolution, the existence of one species is tightly bound up with the life of another species, new or 'improved' adaptations which occur in one species are often followed by the appearance and spread of corresponding features in the other species. These co-adaptational relationships are intrinsically dynamic, and may continue on a trajectory for millions of years, as has occurred in the relationship between flowering plants and

pollinating insects. Co-adaptation and co-evolution, although similar in process, are not the same; *co-adaptation* refers to the interactions between two units, whereas *co-evolution* refers to their evolutionary history;

5. Co-evolution can be pairwise, between exactly two species "A" and "B", or several species may evolve a trait in reciprocity with a trait in another species. This is called *Guild* or *diffuse coevolution*. Where the Guild (or *functional group*) is any group of species that exploit the same resources, or that exploit different resources in related ways. Members of a guild within a given ecosystem could be competing for resources, such as space or light, while cooperating in resisting stresses, attracting pollinators, or detecting predators. In guild co-evolution, several species belonging to a guild may evolve a trait in reciprocity with a trait in another species, as has happened between long-tongued bees and long-tubed flowers.

When the evolutionary process is played at such a scale, the scale above species, we talk about macroevolution.
It is relevant to highlight that the above niche modifications (differentiation and construction) may have as an effect the removal of constraints and creation of opportunities for other species to come. This will increase niche diversity, species interaction and bring forward the process of evolution due to increased species interaction and exploitation of previously un-accessible resources.

### 4.3.4 Biological Interactions and mutualistic networks

Also biological interactions among species have an important role to play in evolutionary process. Interactions can be inter and intra-species. They may involve prey-predator relationships as well as competition and cooperation.
**Competition** is an interaction between organisms or species in which both the organisms or species are harmed when competing for the same resource.
**Co-operation** is the process where groups of organisms work or act together for common or mutual benefits. It is commonly defined as any adaptation that has evolved to increase the reproductive success of the actor's social partners (For example, territorial choruses by male lions discourage intruders and are likely to benefit all contributors). One specific form of cooperation in animals is *kin selection*, which involves animals promoting the reproductive success of their kin (despite they would be competitors within their population), thereby promoting their own fitness. The *inclusive fitness theory* is based on the hypothesis that cooperation helps in transmitting underlying genes to future generations either through increasing the reproductive successes of the individual (direct fitness) or of other individuals who carry the same genes (indirect fitness).
One type of cooperation, **mutualism**, which is the cooperation *between species*, evolves only by enhancing all participants' inclusive fitness. It evolves most readily between members of different kingdoms, which pool complementary abilities for mutual benefit. Among mutualistic processes, there are *symbioses* and *brief exchange mutualisms*. Some of these mutualisms represent major evolutionary innovations (ex: mitochondria in cell's nucleus and the relationship of algae and fungi in lichens).

Biological interaction between species and/or across space can be described via **ecological networks**. An ecological network is a representation of the biotic interactions in an ecosystem, in which species (nodes) are connected by pairwise interactions (links). They are used to describe and compare the structures of real ecosystems, while network models are used to investigate the effects of network structure on properties such as ecosystem stability. They are classified according to their type of ecological interaction, for example, host-parasite networks, trophic networks or mutualistic networks. In particular, **Mutualistic networks** describing inter-guild plant-animal mutualisms (e.g. plant-pollinator) or plant-mycorrhizal interactions have structures characterized by some properties such as:

1. *Nestedness:* It describes a non-random pattern of species interactions where specialist species interact with proper subsets of more generalist species. In highly nested networks, guilds of

species that share an ecological niche contain both generalists (species with many links) and specialists (species with few links, all shared with the generalists). Nestedness is often asymmetrical, with specialists of one guild linked to the generalists of the partner guild.

2. *Modularity*: Networks can have regions of nodes that are more densely connected than others. These regions are called modules or compartments, while less connected regions set the boundaries of the modules. Organisms are generally organized into modules where different subsets of units have a specific functionality. An example is provided by modules of genes involved in development. Modularity reveals the underlying structure in the network, which is relevant to detect groups of significant importance. In ecological networks we can find modules of species that are highly interacting among them but weakly between modules.

Increasing the complexity of a mutualistic network has been reported to increase the resilience of the network to environmental changes (ex: climate change).

Below (Figure 4-3), a representation of a mutualistic network between two guilds, one from plants and the other from animal kingdom.

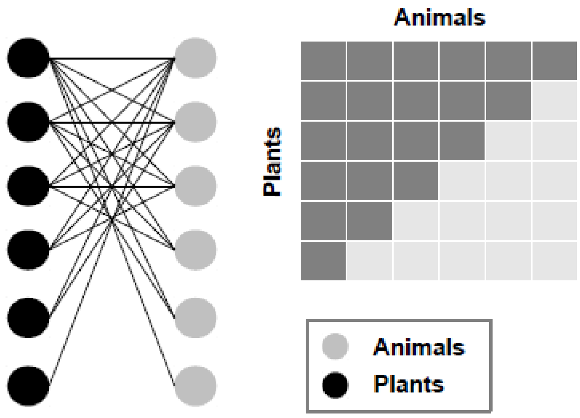



*Figure 4-3: Mutualistic Biological Network. From (Encinas Viso 2013)*

Nested networks. A perfectly nested structure of a mutualistic web is represented by a plant-animal interaction matrix (right side) and a network cartoon (left side). The interaction matrix shows plant species in rows and animal species in columns, where dark grey squares represent observed interactions between a plant and an animal species and light grey squares are non-observed interactions. This matrix is perfectly nested because specialist species form perfect subsets of more generalized species interacting with their mutualistic partners. The right side of the figure shows an explicit representation of the network, where black nodes represent plant species and grey nodes represent animals species and the lines connecting these nodes represent the observed interactions. From (Bastolla et al. 2009; Encinas Viso 2013)

The above representation however does not consider intra-guild interaction but only inter-guild one, where intra-guild interaction is about competition among members of the same guild (ex: animals) for the shared resources in the mutualistic connection with another guild (ex: plants). For intra-guild interaction, the multi-layer approach of Figure 4-4 is proposed:

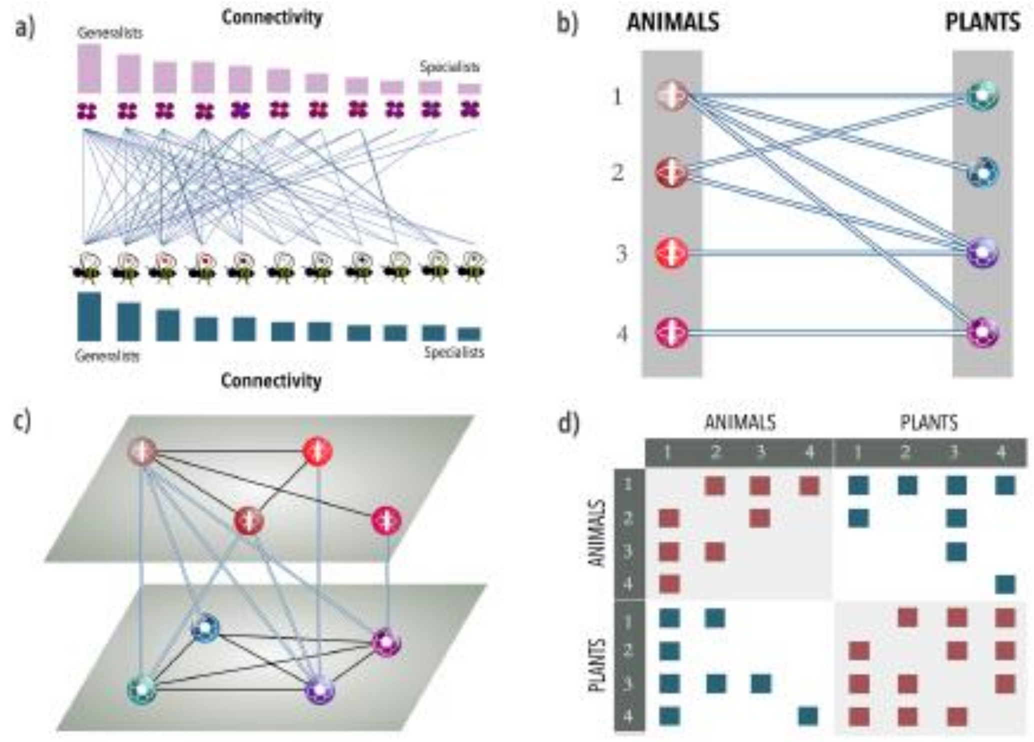



*Figure 4-4: Multilayer (intra and inter-guild) mutualistic network. From (Gracia-Lázaro et al. 2018)*

Panel (a) illustrates a mutualistic system made up by plant and animal species (inter-guild). In this representation, mutualistic interactions are given by the inter-connections among the elements of a bipartite graph, as shown in panel (b) for a synthetic network. Generalists have a higher connectivity than specialists. This representation does not account for intra-guild interactions.
Panel (c) illustrates the multilayer approach proposed for the ecosystem of plants and animals of panel (b), which consists of 4 species of each guild. In this framework, each layer represents one guild and an intra-layer link exists whenever two species of the same guild share the same species of the other guild. These links represent the competition among species of the same guild that are mediated by the mutualistic connections. These two layers are coupled by the mutualistic interactions given by the bipartite graph. Finally, in panel (d) it is depicted the adjacency matrix of the whole system, including both plant-plant and animal-animal competitive interactions (elements of the diagonal blocks in red) in addition to the usual mutualistic links (elements of the off-diagonal blocks in blue). From (Aleta and Moreno 2019; Gracia-Lázaro et al. 2018)

### 4.3.5 Discussion

The analysis carried out reveals, not unexpectedly, the complexity of a topic such as natural evolution. Complexity due not only to the objective intricacy and multi-level inter-connectedness of the processes involved, but also to their speculative nature. Furthermore, the different interpretations and definitions of some basic concepts of biology do not contribute to reduce this complexity.

The investigation seems suggesting that in nature the functions: to *innovate*, to *generate solutions space for novelties emergence* and to *evolve* are connected in a sequence of necessary conditions: to evolve nature needs to innovate and to innovate it needs first to generate solutions spaces for novelties to emerge. However generating these spaces (pools of genetic variability) is not a sufficient condition to have innovations (new inherited phenotypes or novelties) and to be innovative is not a sufficient condition to evolve (evolutionary or adaptive novelties) (see Figure 4-5). What prevents the equality between the two conditions (sufficient and necessary) is the process of *Natural Selection*: those biotic and abiotic factors external to the living system which affect its capacity to transmit novelties to future generations, making them adapted and capable of increasing its fitness, either within its original ecological niche or modifying the environment to create its own new niche.

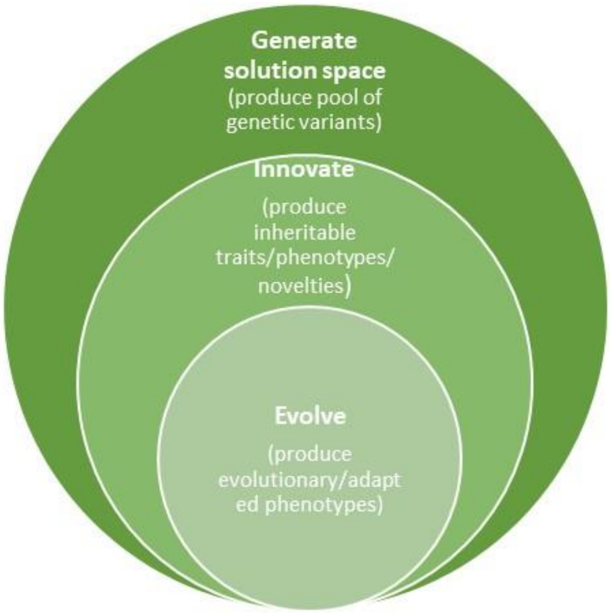



*Figure 4-5: Relations between Generation of solutions space for novelties, Innovation and Evolution in nature as understood by the researcher.*

Novelties, which may or may not become adaptive are triggered by both internal and external factors to the organism. The potentiality for generating novelties (new morphological, physiological and behavioural traits) comes from a continuous production and storing of genetic variations within the genetic material (due to mutation, duplication, errors in replications, etc. ) as well as their exchange among organisms (Horizontal gene transfer). Genetic variations which may not be immediately expressed into a new trait in the organism but be "activated" if and when external conditions trigger them.
Accumulating variations allows to expand the potential *solutions space* where the organism would "search" when the environment requests from it efforts of adaptability (i.e.: to climate changes) or when specific ecological opportunities arise (i.e.: appearance of a new resource to be exploited).
Further than this view, which assumes that the opportunities exploited by evolutionary innovation exist a priori, independently from the organisms, a more recent conceptual framework, not yet largely explored, considers the solution space also *constructed* by the organisms as evolution unfold. New novelties/ innovations emerge through time as a consequence of prior evolutionary changes. Thus, new developmental processes and environmental changes may not represent gaining access to existing but before inaccessible parts of the solutions space, but an expansion of that space with the *construction* of new ecological niches and therefore evolutionary possibilities.

Within this cyclical/non-linear process of generation of evolutionary novelties where they can be both the response to and the cause of external changes, important processes which strongly influence the evolution of the species are biological interactions such as *competition* and *mutualism*. Both have been recognized as engines for evolution and both occur inter and intra-species; with different strategies and also at different time of development. In particular, mutualism can generate co-evolutionary process where two interacting species influence each other evolution during their relationships (for instance pollinating insects and flowering plants). However pairwise coevolution, between exactly two species, is not the only possibility. One form of co-evolution among more species is the *Guild* (or *diffuse*) *Co-evolution,* where an ecological *Guild* is any group of species that exploit the same resources, so competitors, or that exploit different resources in related ways.

Ultimately the process of evolution appears to be a participatory one, in space and time, where the entities belonging to the biological organization (from DNA to ecosystems) are all involved, sometimes with active and sometimes with passive role and where also external abiotic factors are not only affecting evolution but also affected by it.

If genes variations determine the space of possible opportunities for emergence of novelties and subsequently evolutions, these same novelties and evolutions can also allow exploring further that space of possible opportunities, as well as expanding it, creating new avenues for variations within the single organism. Novelties can also allow the generation of new niches outside the organism where new resources appear and become exploitable.

This participatory process can be brought forward through the setting up and evolution of ecological networks; networks of various relationships among organisms. In particular mutualistic networks where different species, also competitors, cooperate for a reciprocal interest.

From the analysis of the various concepts (see details in Annex 2), a preliminary systemic representation of some of them is proposed (Figure 4-6). This, for the benefit of synthetizing a complex issue.

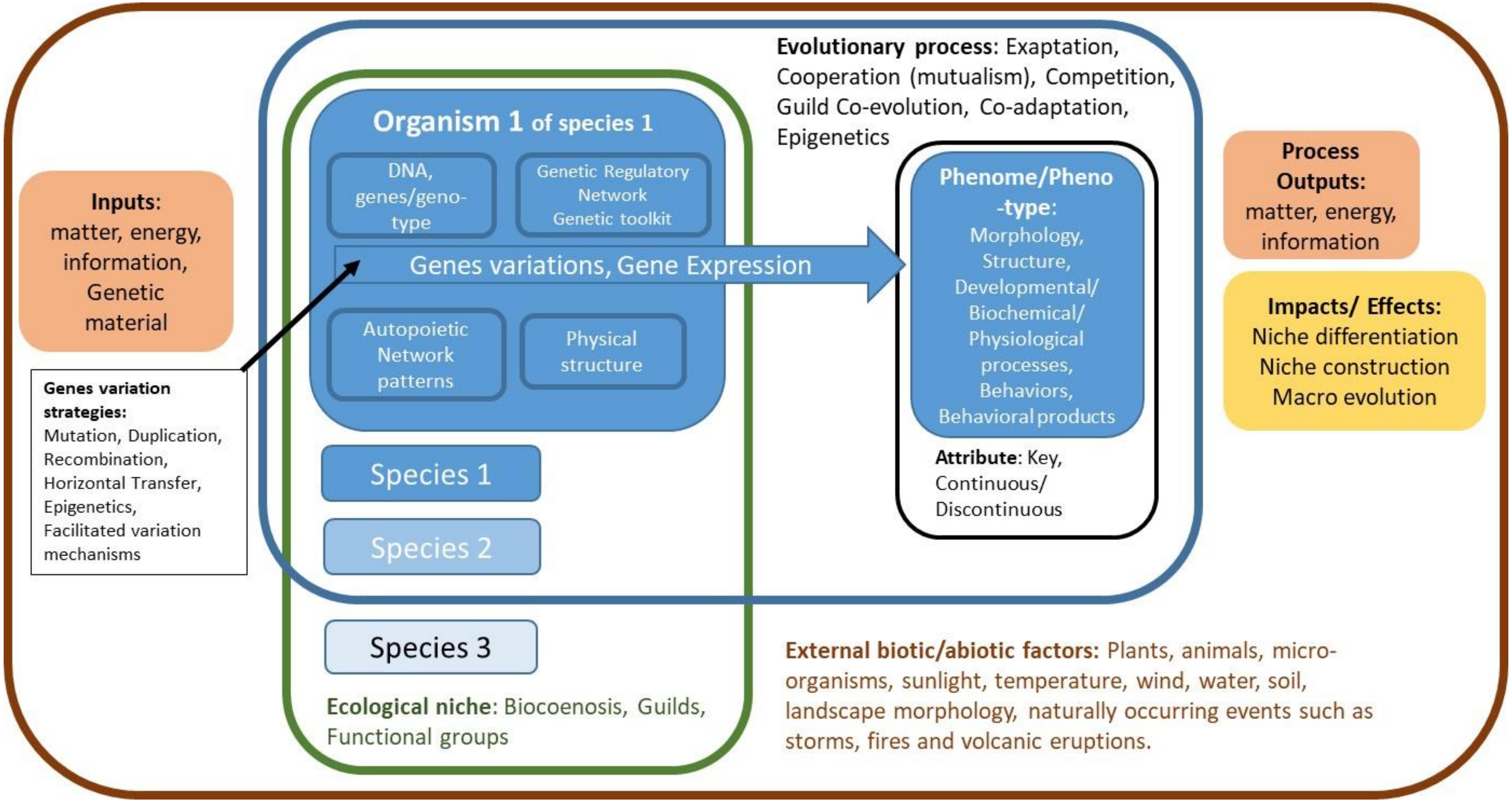



Figure 4-6: *Systemic representation of the Evolutionary process*: *Colour codes, from the external to the inner part of the chart. Brown coloured line represents the existing external conditions which can influence the evolution of a biological system. Biological system which can be represented by a single organism, a species, group of species, a guild and species interacting within a niche – different blue shaded boxes within the green coloured line. The orange coloured box represents the input and output of a biological system. The yellow coloured box represents the impact on the niches and external environment of the biological system. The blue coloured line represents evolutionary processes affecting individual or group of organisms of the same or different species which can modify their phenotypes to increase their fitness. The blue boxes inside Organism 1 represent the main elements for the organism to live and evolve. The blue arrow shows the phases of the phenotypes generation within an organism.*

### 4.3.6 A systemic view of the Innovation Process

The proposition of a systemic view of the evolutionary process of Figure 4-6 gives the opportunity to review the model of *Innovation Ecosystems* described in section 2.2.4 where the analogy with the natural ecosystem is currently faulty (Oh et al. 2016) and could be possibly improved.

The researcher proposes a representation of Innovation Ecosystem based on basic concepts of System Theory which help to mirror the elements and structure of Figure 4-6.

The purpose has not been to match biological concepts with innovation process concepts via a direct analogical transfer, but to utilize concepts from System Theory as a bridge between the two domains. As a first step, concepts associated with Innovation processes have been aligned with concepts of System Theory, concepts that are also present in living systems. This to facilitate the further alignment between natural ecosystems and Innovation ecosystem. To do this the following concepts of Table 4-2 have been considered:

| Concept from System Theory | Definition from System Theory and correspondence in living systems | Associated concept in an Innovation Process |
|---|---|---|
| **System** | A system is a set of related components that work together in a particular environment to perform the functions are required to achieve.<br><br>Living systems are open self-organizing life forms that interact with their environment. | Innovation process is composed of different actors and physical components interconnected and interacting for the purpose of innovating and together forming systems. Depending on the relationships, boundaries, structure and elements necessary to define a system, firms can be seen as systems themselves or simultaneously as components of larger innovation systems. (ex: regional, national, sectoral, etc.) |
| **Holarchy** | Holarchy is hierarchical structure composed of nesting holons, which are elements that are simultaneously a whole and a part.<br><br>Holarchy are typical in living systems. | A firm can be a system in itself with nested sub-systems representing departments, branches, suppliers etc. and at the same time it could be a component of a larger nested system formed by several firms operating for a common purpose (ex: regional, national, sectoral system, etc.) |
| **Components** | Components are the operating parts of a system.<br><br>A Living system is an assembly of parts operating together to guarantee the existence of the system itself and the achievement of its functions. Parts are phenotypes/traits, all the characters defining the living system and subject to evolution. | In Innovation process, the components are the tangible and intangible assets (know-how, human-resources, physical structure) which define the firm or group of firms and are necessary to innovate.<br>This includes also the generated innovation itself (product, service, etc.) |
| **Relationships** | Relationships are the links between the components.<br><br>All parts of a living system are connected by a multi-levelled network of relationships. | All possible contractual or non-contractual relationships among the actors within a firm or group of firms while innovating (ex: with suppliers, employees, utility companies) as well as possible temporary/lasting relationships with actors from the external environment (ex: new suppliers, public |

| Concept from System Theory | Definition from System Theory and correspondence in living systems | Associated concept in an Innovation Process |
|---|---|---|
| | | entities, consumers associations) which therefore become part of a larger system. |
| **Attributes** | Attributes are the properties of the components and the relationships between them; they characterise the system.<br><br>In living systems, phenotypes/traits have various attributes. | In particular the focus is on attribute of the type of innovation such as incremental (continuous) and radical (breakthrough/discontinuous). |
| **Inputs/ Output** | Input is something put into a system or expended in its operation to achieve output or a result. Output is the information produced by a system or process from a specific input.<br><br>Living systems, being open-self organizing system, are maintained by flows of information, energy and matter and produce as well information, energy and matter as outputs. | *Input*: all the resources needed by the firm or group of firms to carry out their main function of innovating.<br>*Output*: all the by-products of the innovation process (wastes, ideas, values, etc.) generated by the firm or group of firms aside the innovative products. |
| **Open system** | Open systems have input and output flows, representing exchanges of matter, energy or information with its surroundings.<br><br>Living systems are open self-organizing life systems. | Innovation systems are open systems as they exchange matter and energy with the external environment to maintain their equilibrium. |
| **Boundaries** | A system boundary may be thought of as the point at which data flows from one system to another. The degree to which data is free to flow from one system to another is known as the permeability of the boundary.<br><br>Living systems are organized according to biological organization (cells, organs, organisms, species, ecosystems, etc.). Each level has its own boundaries. | Innovation systems have several boundaries depending on the components and their interaction (departments, firms, group of firms, value-chain firms, innovation systems, etc.). |
| **Patterns of organization** | The configuration of relationships (that can be mapped) that determine the system's essential characteristics (the "identity" of the system).<br>System's organization is independent on the properties of its components, so that a given organization can be embodied in many different manners by many different kinds of components. | Social and Organizational structure within a firm or among a group of firms which represents the configuration of relationships among the components within a firm or group of firms. For instance: departments' structures, production process structure, relationships with the value chain, etc.<br>This also includes all the rules, standards, values to which the firms abide and which are necessary for the existence and functioning of the social and organizational structure. |

| Concept from System Theory | Definition from System Theory and correspondence in living systems | Associated concept in an Innovation Process |
|---|---|---|
| | For living systems the patterns of organization is *Autopoietic* (self-making), where the components of the system are produced by other components (so organizationally closed system). | |
| **Structure** | Physical embodiment of the system's pattern of organization.<br><br>Living systems have physical structure. | The physical component in a firm or group of firms such as technologies, equipment, buildings, logistical means, etc. |
| **Internal Environment** | A system operates in an environment with both internal and external components. Its internal environment is that part of its environment over which it has some control.<br><br>For a living system, the internal environment can be represented by the physical structure and all the processes occurring in its development and growth. | The internal actors, physical, organizational structures and know-how of firm or group of firms while innovating. The actors have control on these components. |
| **External Environment** | A system's external environment is that part of its environment over which it has no control, but it still affects the requirements of the system.<br><br>Living systems interact with their environment and are affected by it. | All external Social and Environmental conditions which influence a firm or a group of firms in their endeavour of innovating and for which they have to respond and adapt. |

*Table 4-2: Correspondence between elements of System Theory/Living systems and Innovation process/systems – elaborated by the researcher – source for System Theory and Living system:* (Capra and Luisi 2014; Capra 2002; Meadows 2009), *(Mella 2009)*

Based on the definitions above, the researcher proposes an organic/systemic representation of the Innovation (Eco)System as in Figure 4-7, which is more aligned with the eco-systemic representation of Figure 4-6.
The researcher believes that this representation could serve to the following purposes:

1. to visualize in a more organic and connected way all the concepts described in Chapter 2 (and Annex 1) which define the "universe" of Innovation processes (as highlighted in section2.2.1);
2. To reduce the fallacy of the previous use of the biological analogy of ecosystem to define Innovation Ecosystems (as highlighted in 2.2.4) as well to review and generate more accurate and useful biological analogies at system level for other existing biological analogies such as "Business Ecosystem", "Industrial Symbiosis" "Technological evolution", "Evolutionary Innovation", "Evolutionary Economics", etc.;
3. To facilitate future multi-sectoral research not only in Innovation Systems and Management but also and more interestingly in bio-inspired models and frameworks of innovation utilizing biological analogies at (eco)system level (lack of current BID methods highlighted in section 2.3.3).

To the best knowledge of the researcher, this was never attempted before but it needs to be highlighted that this conceptualization based on the information gathered in Chapter 2, has not been demonstrated.

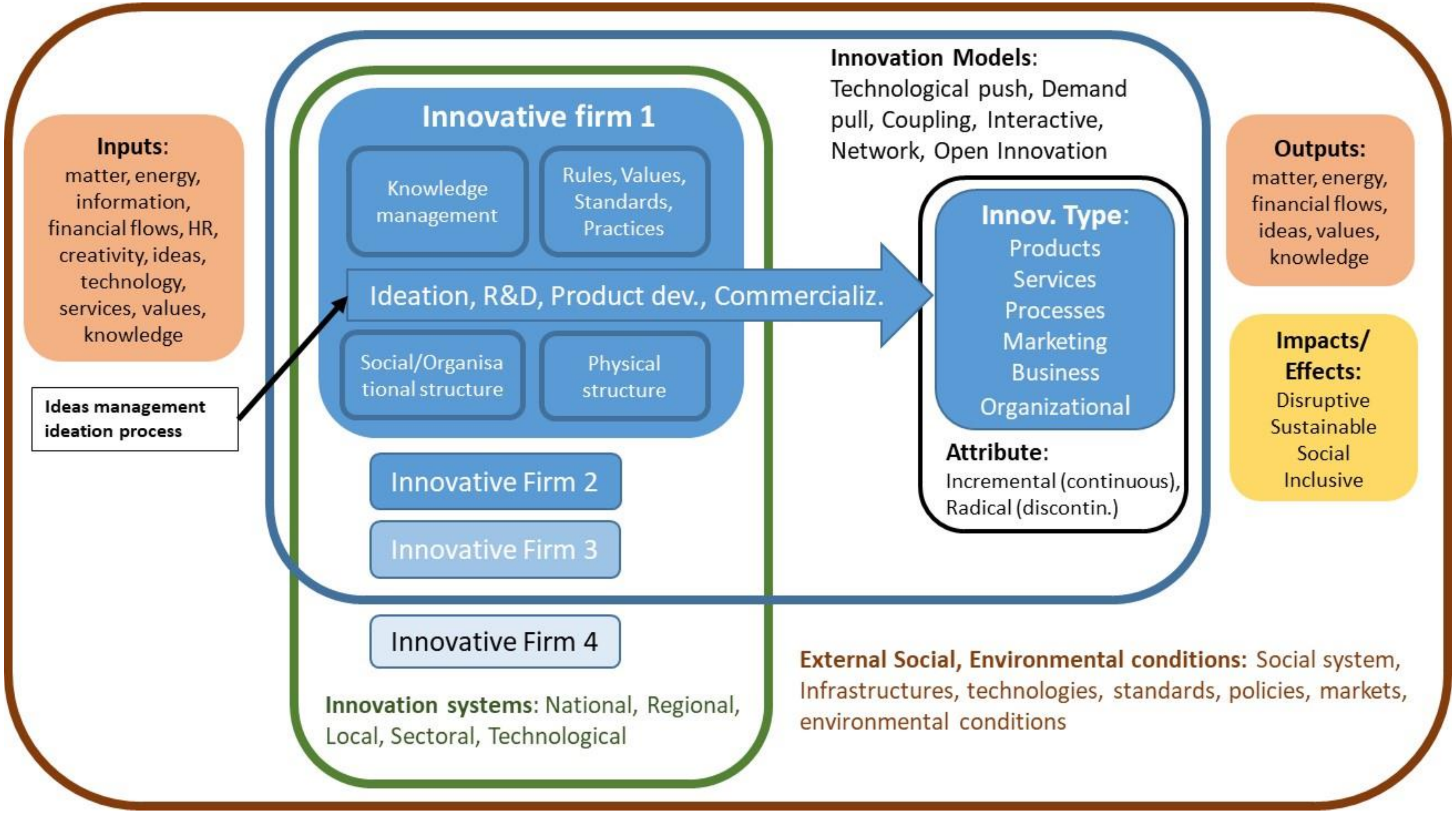



*Figure 4-7: Representation of Innovation Ecosystem: Colour codes, from the external to the inner part of the chart. The brown coloured line represents the existing external conditions which can influence the Innovation Ecosystem. The orange coloured boxes represent the input and output of the system; the yellow coloured box represents the impact of the system on the external environment. The green coloured line represents how innovating firms can cooperate (at different geographical and sectorial scale) with other entities such as other firms from similar or different sectors as well as other non-commercial entities. The blue coloured line represents all the activities carried out by individual or group of firms of the supply chain or/and competitors in order to achieve alone or together some innovative products. The blue boxes inside Firm 1 represent the main elements for the firm to operate. The blue arrow shows the phases of the innovation process highlighting the location of Ideas management/ideation process.*

## 4.4 Principles Extraction

Despite the biological concepts explored were numerous, only some of them have been considered interesting for this research when connecting ideas generation with the innovation process.
In reminding that the initial problem defined in section 4.1 was to identify principles which could fulfil functions such as: "to generate novel ideas" and "to innovate", Table 4-3 lists the principles extracted from biological solutions whose application could potentially improve the fulfilment of the functions. As already mentioned in the Chapter 3, the extraction has been carried out by the researcher and it is therefore affected by subjectivity.

It is important to specify that in this process of analogical transfer, the researcher tried to disconnect as much as possible from physical structures and entities and concentrate on the functionalities. A direct link between actors and factors in natural evolution and actors and factors in human innovation could lead to ill-conceived and not effective analogies (for instance considering the firm as one organism would not allow extending it coherently when moving to the level of "species").

*Table 4-3: Principles extracted from biological solutions*

| Biological Solution | Extracted Design Principle |
|---|---|
| *Evolutionary process*<br><br>Continuous;<br>Across the biological organization;<br>Through interactions with biotic and abiotic factors | Innovation process that happens continuously, involving actors and factors within and outside any classical innovating agent.<br>No compartmentalization of the innovation process neither clear definition of the innovating agent; all entities, including the external environment, are both innovating and subject to innovation.<br>Boundaries among the classical phases of the innovation process are removed as well as internal boundaries such as physical structure, organizational structure, human resources and boundaries with the external environment. |
| *Genes variations and related mechanisms*<br><br>Build up pool of genes with variants; continuously and transmit them to future generations for potential future expression. | *Build up and replenish the repository of knowledge for Ideas.*<br>As the pool of genes is the basic material upon which new genes variants can be generated, in a firm there should be a repository of knowledge though which new ideas are generated. This could be the know-how of the firm and, in case of BID, biological knowledge upon which the firm can generate bio-inspired idea. The repository of knowledge can be expanded with knowledge from inside and outside.<br><br>*Continuous generation of ideas*.<br>Ideas should be generated continuously though a well-established process even if not all necessarily find their way to R&D and Product Development. This would allow expanding the range of potential solutions when problems occur and when conditions will be mature for certain ideas to become products and access the market. This can increase potential for innovation and resilience of a business.<br><br>*Set up Ideas management system*.<br>Even if not immediately utilized, or considered as mistakes, the ideas should be stored and easily retrievable in case opportunities arise for their utilization.<br>New ideas could derive from: expanding the potential solution space with new know-how, internal recombination of existing knowledge, exchange of ideas and know-how with external sources and mistakes. |
| *Epigenetic factors* | *External factor triggering changes in the process of ideas generation*.<br>In particular triggering change in the use of exiting know-how (no increase of know-how) or the use of non-mainstreamed ideas (or the interruption of use of previously mainstreamed ones). Changes can be |

| Biological Solution | Extracted Design Principle |
|---|---|
| Gene variation and expression triggered by external factors to the organism. | temporary or permanent and can affect all business process: know-how, ideas, organizational structure, production process, market strategy etc., incrementally or radically.<br>External factors can be external to the firms as well as usually external to the ideation process (ex: customers or suppliers) but still internal to the firm (different departments). |
| *Generation of novelties*<br><br>Genes variants can be expressed into new phenotypes which can be adapted to existing conditions increasing fitness of the organism or trigger changes at ecological niche level. | *Generate ideas for both incrementally and radically new concepts*.<br>Both incrementally and radically new ideas can generate opportunities for development of new and previously unexplored markets and resources. Innovation is not only about *searching* for diversified products to exploit existing un-exploited market niches but it is also about *constructing* not yet existing market opportunities. |
| *Guild – Functional group*<br><br>Organisms within an ecosystem carrying out similar function or competing for the sae resource | *Identify Business Guilds.*<br>Businesses from the same sector, therefore exploiting the same market niche (competitors) or exploiting different market segments in related ways (ex: filtering systems but for different type of customers). Therefore, members of a Business guild do not need to exploit the same market segment. They can be competitors in a specific market niche while cooperating for achieving further benefits (access to resources or market's segments) or responding to crises. |
| *Guild/Diffuse Co-evolution*<br><br>Reciprocal evolution among a functional group of species (guild) rather than exactly two | *Set up Business guilds.*<br>Business "guilds" can directly co-evolve together in pairs and in groups (one of the members evolve and the other follow). Exerting innovation on each other. |
| *Exaptation/co-option*<br><br>Natural selection finds new uses (functions) for existing traits including genes, organs, body structures and behaviours. | *Use same products for different purposes* (functions).<br>Use same know-how and production process to generate new design concepts and develop new products. |
| *Co-evolution*<br>*Co-adaptation*<br><br>Cooperative or competing species exerting selective pressures on each other, affecting each other's evolution;<br>The emergence of new or improved adaptations in one species followed by its appearance in the other species. | *Co-evolve.*<br>Synchronous or asynchronous generation of internal changes and/or of new products in connected/interacting businesses. For instance between TIER1 and TIER2 firms.<br>Interactions/relationships causing reciprocal push for incremental or radical innovation (in terms of products or/and internal organizational structure). More links and relationships and more chances for co-evolution. |
| *Niche Construction*<br><br>The activities of organisms, modify or stabilize environmental states, and thereby affect natural selection acting on themselves and other species. | *Niche Construction.*<br>The activity of the business modifies the environment within which it operates. This can concerns changes in the market with opening of new market niches via new products but also changing customers' attitude, relations with suppliers and competitors and policy changes. The external changes can generate also internal changes to the business. |
| *Mutualism* | *Set up Business Mutualisms*. |

| Biological Solution | Extracted Design Principle |
|---|---|
| Cooperation between species enhancing all participants' fitness;<br>With/without division of labour (see Annex 2 – mutualism);<br>Cooperation also among competitive species (Kin selection) | Businesses bringing their own abilities for the benefits of all. There can be the following forms of mutualism:<br>A. Mutualism without division of labour: each business does its own operations in a common action where benefits are shared. Cheating can happens (but not detrimental to the non-cheater)<br>B. Mutualism with division of labour:<br>*Symbiosis* (long-term): Partners' fidelity, choice of partners and partners sanction if cheating.<br>*Brief exchange mutualism* (short-term): limited partner choice, partners sanctions applied.<br><br>*Define and set up Coopetitive Strategy.*<br>Strategies where competitors (for instance firms belonging to the same business guild) simultaneously cooperate and compete with each other. Coopetition that does not put core competence of partners at risk. Coopetition can be among firms but also within a firm among competing departments. |
| *Mutualistic Networks*<br><br>Networks of cooperative biological interaction between species; specialist and generalist species | *Set up Mutualistic Networks.*<br>In order to exploit benefits of mutualism, multi-layer mutualistic networks can be set up where layers of competing firms (business guild) are connected in mutualistic relationships with competing firms (or customers) from another layer.<br>Members of each layer can be multi-corporations (generalists) and specialized firms (specialists) where multi-corporations exploit different markets with different products and specialized firms address single market segments. Multi-corporation can absorb loss of markets segments (due to loss of customers as well as loss of some suppliers affecting production) because of their products differentiation. |

Many of the principles extracted in table 4-3 are in fact related to already existing best practices linking the ideation phase and innovation process as described in Chapter 2 (and Annex 1). It is therefore not the intention of the researcher to propose any new practice, but rather to highlight, among many practices adopted in different contexts, those ones that find a correspondent analogous in nature.
It is however the opinion of the research that further exploring natural evolutionary processes may provide more opportunities to extract principles for defining and testing new practices in innovation management.

# 5 – PRINCIPLES APPLICABILITY

## 5.1 BID-friendly Innovation Models

The principles extracted in section 4.4 allow proposing and answer to Sub-question n.1 hereby re-proposed:

*Which framework of innovation model would enhance the synergy between BID and the Innovation process so as to increase the effectiveness of BID as tool for innovation?*

In general, the main aspect that could be highlighted from the analysis of the process of generation of biological novelties and evolution, is that this process happens continuously, involving actors and factors within and outside any level of the biological organization. Furthermore, in nature there is no compartmentalization of the evolution process neither a clearly identified and unique agent responsible for evolution; all entities, including the external environment, are both evolving and subject to evolution.
Starting from this broad consideration of the evolutionary process as biological analogous, a process of innovation within a firm could be imagined where generation of ideas and innovation is continuous; where segregation of the ideation process to a single department does not occur and the ideation phase is connected with the other phases of the innovation process; an innovation process where ideation is influenced by internal as well as external actors and factors to the firm.

Therefore the researcher proposes a concept for a model for innovation named *Evolutionary Innovation Model* which:

1. Is based on already existing best practices of innovation management applied in different contexts; practices which however find correspondent biological analogies which are connected to the broader process of natural evolution;
2. Aims at collecting and organising these best practices in a more organic/systemic way, following the natural evolutionary process as biological analogous;
3. Proposes practices which promote the connection between the ideation phase (and its methods and tools including BID) and other phases of the innovation process.

It is reiterated that the contribute of the researcher has not been to propose new practices of innovation management, but rather to evaluate existing practices against biological principles related to the evolutionary process and consequently select the practices which better comply with such principles, giving them an organic structure.

### 5.1.1 The Evolutionary Innovation Model (EIM) framework

Because of the objects of the research question, BID methods and business sector, the entity playing the leading role in the innovation process is hereby considered *the firm*. Furthermore, it is important to highlight that the formulation of the model focuses exclusively on the connection between the ideation process and the other innovation phases. It does not expand on other innovation phases and their connections. An expanded framework of the EIM could be possible exploring further biological principles related to evolutionary processes whose abstraction would concern phases such as R&D, Product Development and Commercialization; however, this is not the object of this research.

Based on this, the EIM framework is divided between an internal and external framework:

- The *internal framework* concerns the process of ideas generation which occurs within a single firm;

- The *external framework* concerns the process of ideas generation which involves the firm and other actors external to the firm.

The operating principles of the ***EIM Internal framework***:

- *Build up and replenish the repository of knowledge for Ideas:* As the pool of genes is the basic material upon which new genes variants can be generated, in a firm there should be a repository of knowledge though which new ideas are generated. This could be the know-how of the firm and, in case of BID, biological knowledge upon which the firm can generate bio-inspired idea. The repository of knowledge can be expanded with knowledge from inside and outside.
- *Continuous generation of ideas*. Ideas should be generated continuously though a well-established process even if not all necessarily find their way to R&D and Product Development. This would allow expanding the range of potential solutions when problems occur and when conditions will be mature for certain ideas to become products and access the market. This can increase potential for innovation and resilience of a business.
- *Set up Ideas management system*. Even if not immediately utilized, or considered as mistakes, the ideas should be stored and easily retrievable in case opportunities arise for their utilization.
- *Generate both incrementally and radically new concepts.* Both incrementally and radically new ideas can generate opportunities for development of new and previously unexplored markets and resources. Innovation is not only about *searching* for diversified products to exploit existing un-exploited market niches but it is also about *constructing* not yet existing market opportunities. In this respect, BID methods, among all ideas generation methods, can provide material upon which more radically new concepts can be generated.
- *Generate ideas with participatory process*. The ideas generation process has to be carried out with the involvement of all internal departments of a firm, including managers. Therefore, it has to be conducted with information and procedure which can be understood by multi-disciplinary teams and be embedded in the culture of the firm. In this respect, the utilization of BID and properly organized biological knowledge, could allow the participation to the ideation process of non-technical staff providing their creative contribute. Ideas which can become innovation do not generate from a single dedicated entity but it is a synergic activity which involves inputs and influences within and outside the firm. This process can be enhanced via:
  - *Cross-pollination.* Cross-pollination of ideas generated within and outside the firm.
  - *Use of Communities of Practice* within the firm (Swan, Scarbrough, and Robertson 2002)
- *Generate Co-opted Ideas.* Use same know-how and production processes to generate new design concepts and develop new products. Also, use same products for different purposes (functions).

The operating principles of the ***EIM External framework***:

- *Be Guild-based or Sectoral*. The EIM applies to sectoral innovation systems. Innovation agents connected within the same sector (same market or segments of the same markets) either as part of the supply chain or/and as competitors. Customers are included.
- *Follow Coopetitive – Open Innovation principles*. The ideation process can to be carried out according to principles and practices of Coopetitive Open Innovation models. This type of model allows networked partners to gain mutual benefits from the process (optimized benefits/costs ration of the ideation process). Costs for producing the basic knowledge (analogy with the pool of genes variants) from which the ideas are generated shall be shared among partners as well as the possibility to utilize it to generate ideas.
- *Basic Knowledge meaningful to all partners*. The basic knowledge from which the ideas are generated has to be organized to be understandable and usable by the partners. For instance, when a BID ideation process is utilized, biological knowledge shall be retrieved and organized so as to be meaningful to specific sectoral partners. This, with the objective to optimize benefit/cost of retrieving and utilizing biological information (avoid exploring irrelevant biological strategies).

- *Set up Mutualistic networks.* Cooperating actors in the ideation process can be organized as multi-layer mutualistic networks. For instance, network with actors belonging to TIER 1, 2 and 3 as well as customers (Figure 5-1). Where Tier 3 companies process and provide the required raw materials; Tier 2 companies use the raw materials to make parts of the final product and Tier 1 companies assemble the parts into the final product to sell it to customers (which could be also Original Equipment Manufacturers).

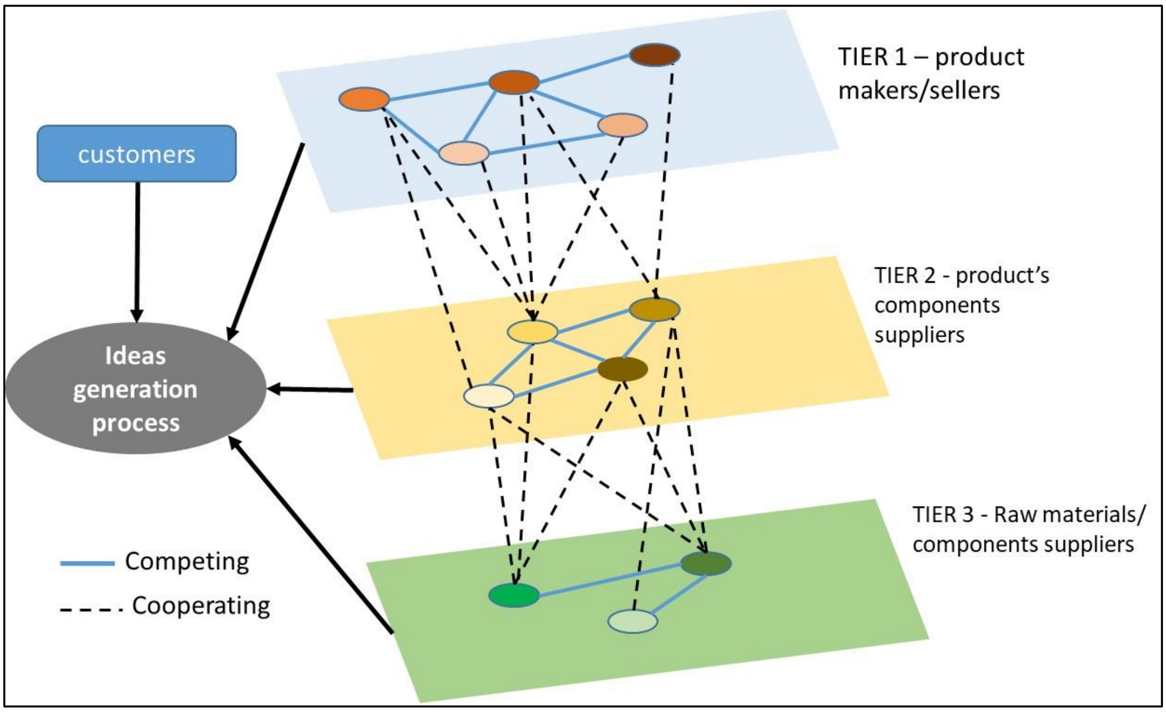



*Figure 5-1: Representation of the Evolutionary Innovation Model for TIER 1 to TIER 3 partners. Firms competing within one level but cooperating across levels.*

## 5.2 BID methods more suitable for the Industrial sector

Some of the principles extracted in section 4.4, in combination with relevant *solving strategies* identified in section 3.2.3, allow proposing a preliminary answer to Research Sub-question n.2 hereby re-proposed:

2. *Which type and amount of biological information should be considered in a BID tool and how to structure it so as to increase the effectiveness of the BID process in terms of ideation metrics?*

As a first step, a list of the principles considered relevant to elaborate at the level of BID methods and tools is drafted:

| Biological solutions | Extracted Design Principles (selected from section 4.4) |
|---|---|
| **Genes variations and related mechanisms** | 1. Allow Building up and replenish the repository of knowledge for Ideas |
| **Guild/Diffuse-Coevolution** | 2. Useful to specific Business "guilds" – Industrial Sectors |
| **Key Factors** | **Solving Strategies (from section 3.2.3)** |
| **Modality in Representation** | 3. Introduce mixed modalities in representation including visual and textual one |
| **Expertise** | 4. Engage experts in the domain of the problem in the ideation process |

| | |
|---|---|
| **Cognitive aspects** | 5. Provide both generalized and detailed description of the biological phenomena<br>6. Present diverse stimuli linked to shared principles (multiple analogues)<br>7. Incorporate structures of categories of information |
| **Computational Synthesis/ Automation** | 8. Be expandable in biological entries for addressing specific problems (automated or not) |
| **Problem/Solution-driven approach** | 9. Allow for both problem and solution driven approach |
| **Awareness and managerial support** | 10. Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process |
| **Multi-disciplinarity in design team** | 11. Provide extracted design principles of biological solutions |
| **Problem Contextualization** | 12. Embed biological information of function's object and context which can relate with problem's context and requirements |
| **Scalability of biological mechanisms** | 13. Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms |

*Table 5-1: Combined list of relevant Solving Strategies and Extracted Principles to be apply to design BID methods.*

As already explained in section 3.2.5, two additional extracted principles from section 4.4 were added (n.1 and 2 in Table 5-1) as they are related to the ideation process and its actors and they can have an influence on the structure and applicability of BID methods especially in the business sector.
To simplify the discussion, from now on the combination of the twelve solving strategies and the two extracted principles selected is reported as "*BID methods' Design Principles*".

Based on the above principles, an analysis has been carried out to assess the compliance of existing BID methods and tools with the principles. With this approach it can be assessed:

- If there are already fully compliant BID methods or tools which therefore could be more suitable to be utilized by the business sector and within the framework of the EIM;
- If there are partially compliant BID methods and tools which could complement each other in order to fulfil all the principles;
- If there are partially compliant BID methods and tools which could be modified to become fully compliant;
- If there is the need to develop a new BID method which could be fully compliant.

The assessment, described as considered the most frequently researched and used BID methods:

| **BID methods' Design Principles**<br>*From section 4.4 and section 3.2.3* | Biomimicry Thinking/ Asknature Method and Database | SBF-DANE Method and Database | BIOTRIZ Method and Database | SAPPhIRE – IDEA-INSPIRE Method and Database | Engineering to-Biology Thesaurus and Function-based BID Method and Database | FIND-STRUCTURE Method and Database |
|---|---|---|---|---|---|---|
| 1. Allow Building up and replenish a repository of knowledge for Ideas | Database accessible and can be upgraded by external users. Knowledge from various sources lightly edited (Baumeister and et Al. 2011) | Database accessible but cannot be upgrade by external users. Knowledge to be processed in the SBF model (Goel, Rugaber, and Vattam 2009) | Database not accessible Knowledge to be processed according to (Vincent et al. 2005) | Database not accessible Knowledge to be processed in the SAPPhiRE model (Chakrabarti et al. 2017b) | Database not accessible. Knowledge to be processed in the Function-based BID (R. L. Nagel et al. 2008) | Database not accessible. Knowledge need to be processed and mainly on structures (Helfman Cohen, Reich, and Greenberg 2014a) |
| 2. Useful to specific Business "guilds" – Industrial Sectors | Already useful thanks to more than 1700 biological solutions for 162 functions (at 03/20) | Possible if relevant biological solutions are introduced. So far only 22 available (at 03/20) | Already useful thanks to the use of TRIZ inventive principles | Possible if relevant biological solutions are introduced. | Possible if relevant biological solutions are identified | Partial – only biological solutions concerning structures are included (from 140 organisms) |
| 3. Introduce mixed modalities in the representation of the biological solution including visual and textual one | YES - Information extracted from biology literature when available | YES - Information extracted from biology literature when available | YES - according to the reference but could not be confirmed as database not accessible | YES - Information extracted from biology literature when available | Cannot be assessed from existing references | YES - Information extracted from biology literature when available |
| 4. Engage experts in the domain of the problem in the ideation process | Possible – minor training needed for consulting the database | Possible - Training needed in SBF model | Possible - Training needed in TRIZ and BIOTRIZ | Possible - Training needed in SAPPhIRE model | Possible – minor training needed in Function-based model | Possible – minor training needed for consulting the database |
| 5. Provide both generalized and detailed description of the biological phenomena | Partially - It depends on the biological solution | YES – details in form of SBF model | YES according to the reference but could not be confirmed | YES - details in form of Sapphire model | Cannot be assessed from existing references | Cannot be assessed from existing references |
| 6. Present diverse stimuli linked to shared principles (multiple analogues) | YES - multiple analogues deploying similar strategy to carry out the function | Possible if relevant biological solutions are introduced. So far only 22 available | YES – principles derived from multiple analogues but analogues not accessible | Possible if relevant biological solutions are introduced. | YES – multiple analogue available in the Eng-to-Bio. Thesaurus Also possible in the function-based BID database if relevant biological solutions are introduced | YES structure-function patterns derived from multiple analogues |
| 7. Incorporate structures of categories of information | YES – so far only at Functions level though (Biomimicry Taxonomy) | YES - as foreseen by the SBF model | YES - as foreseen by (Vincent et al. 2005) | YES - as foreseen by the SAPPHiRE model | YES – as foreseen by the Function based model | YES – as foreseen by the Structure-Function approach |
| 8. Be expandable in biological entries for addressing specific problems (automated or not) | YES – by external users too. usually crowd-sourcing (not automated) | YES but by the developer as software not accessible only for browsing and not editing | YES but by the developer as software not accessible | YES but by the developer as software not accessible | YES but by the developer as software not accessible | YES but by the developer as software not accessible only for browsing and not editing |
| 9. Allow for both problem and solution driven approach | YES already – wide range of problems can be | Possible but so far limited range of | Possible for solution driven if database is | Possible for both if database is accessible. | Possible for both if database is accessible | Possible for both though limited to current |

| **BID methods' Design Principles** *From section 4.4 and section 3.2.3* | Biomimicry Thinking/ Asknature Method and Database | SBF-DANE Method and Database | BIOTRIZ Method and Database | SAPPhIRE – IDEA-INSPIRE Method and Database | Engineering to-Biology Thesaurus and Function-based BID Method and Database | FIND-STRUCTURE Method and Database |
|---|---|---|---|---|---|---|
| | addressed thanks to more than 1700 entries | problems can be addressed due to limited entries | accessible. Currently suitable for problem-driven | Unknown current amount of entries | though appear more suitable for problem-driven | structure-function patterns available |
| 10. Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process and acknowledging them | YES – tested with multidisciplinary teams including managers (through the Global Biomimicry Design challenge) | Not reported | YES – tested in ideation workshops but with BioTRIZ facilitators | Not reported | Not reported | Not reported |
| 11. Provide extracted principles of biological solutions | Not available – only description of the biological strategy in biology terms | Not available – biological model according to SBF model which is in biology terms | YES – in terms of TRIZ inventive principles | Not available – biological model which is in biology terms (though Sapphire model tested to be used for transfer) (Sartori, Pal, and Chakrabarti 2010) | Not available – biological model which is not in biology terms | YES – according to structure-function patterns |
| 12. Embed biological information of function's object and context which can relate with problem's context and requirements | Not specifically addressed | Not specifically addressed | Not specifically addressed | Not specifically addressed | Not specifically addressed | Not specifically addressed |
| 13. Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms | Already possible due to 1700 analogues available | Very limited with currently available entries in the database. | BIOTRIZ already based on multiple analogues and principles extracted are scale-independent | It cannot be assessed as database is not accessible | It cannot be assessed as database is not accessible | Already possible but limited by the total of 140 entries |

*Table 5-2: Assessment of compliance with 13 BID methods' design principles of most frequently researched BID methods and tools.*

Following the analysis reported in Table 5-2 a discussion on some of the design principles is provided in Table 5-3 below:

| BID methods' Design Principles | Discussion |
|---|---|
| 1. Allow Building up and replenish a repository of knowledge for Ideas<br>2. Useful to specific Business "guilds" – Industrial Sectors | AskNature already counts on an accessible repository of more than 1700 biological solutions. Find-Structure is also accessible and it is based so far on 140 biological solutions organized according to structure-function patterns. Other BID Databases are not accessible. Some of their architectures could be replicated because connected with well defined ontologies (for instance SBF-DANE and IDEA-INSPIRE) and biological information would have to be retrieved from other sources and processed according to the specific functional/biological model. DANE provides a software to encode biological models but currently only 22 are publicly available and the encoding function is not active. IDEA-ISPIRE is not accessible.<br><br>Therefore, AskNature is the only accessible biological database ready to address several problems due to its rich taxonomy and biological solutions. The accessibility would favour AskNature over DANE and IDEA-INSPIRE because AskNature does not have a pre-fixed structure to store biological information. The immediate usability with several biological entries free of charge would also favour AskNature even if benefits were unknown. |
| 4. Engage experts in the domain of the problem in the ideation process | AskNature (and the related Biomimicry Thinking approach) are easy to be understood and do not require the setting up of biological models.<br>The rather intuitive use allowing people with different background to consult it could favour AskNature over other BID methods even if benefits are unknown. |
| 5. Provide both generalized and detailed description of the biological phenomena | The information in AskNature is not structured and not uniform across the several biological solutions. This, depending on the problem to be solved, may require further investigation in biological literature to better understand the biology and retrieve meaningful information for the process of extraction of design principle. The information in DANE and IDEA-INSPIRED are well structured according to the SBF and SAPPhIRE models.<br><br>The lack of structured information and different level of details of the biological solutions in AskNature may convince for a more structured approach. This could be done using DANE and SAPPhIRE formalism or a customized database with fields of information considered relevant. |
| 10. Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process | Access and type to information and simplicity of methods are crucial to allow non-technician participating to the idea generation process. In this respect AskNature is the only one that has been proven suitable for multi-disciplinary consultation<br><br>Adaptability to customized formats, more managers-friendly, would favour the use of AskNature over other BID methods and databases or a customized database with manager-friendly information. |
| 11. Provide extracted design principles of biological solutions | AskNature provides only the biological solutions without extracting design principles. In addition, the functional taxonomy refers to biological functions. The Biomimicry Thinking methodology (also conceived by the developers of AskNature) provides only the following indication:<br>"*The next step of abstracting is the translation from the biological mechanism to a design principle. A design principle, like a function, lingers in the neutral territory that does not belong exclusively to biology, engineering, business, or any other discipline. Rather, it captures the essence of the biological strategy and translates it in such a way that is biologically accurate, but devoid of confusing biological jargon. Think of it as saying exactly the same thing, but without any obvious connection to biology."* (Baumeister and et Al. 2011)<br><br>Find-Structure provide broad extracted principles in terms of structure-function patterns; DANE and IDEA-INSPIRE provide biological models but not extracted principles though Sapphire has been adjusted and tested for this purpose (Sartori, Pal, and Chakrabarti 2010)<br><br>None of the BID methods and tools but Find-Structure currently provides extracted design principles However principles are in form of broad structure-function patterns and can limit the range of problems that can be addressed. Providing extracted principles has a cost. |

| BID methods' Design Principles | Discussion |
|---|---|
| 12. Embed biological information of function's object and context which can relate with problem's context and requirements | None of the BID methods seem addressing the issue of providing relevant biological knowledge specific to the problem to be solved and its requirements but the functional or biological model.<br>A customized database may be considered, which is tailored on specific problems and which could serve a specific business sector. |
| 13. Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms | In general, because of its database populated by more of 1700 biological solutions, AskNature can be already utilized by many business sectors and free of charge. While other Biological repositories would need to be filled up at a cost.<br><br>The immediate usability with several biological entries free of charge would favour AskNature even if benefits were unknown. |

*Table 5-3: Discussion around the results of the analysis of Tab 5-2 for specific design principles.*

The above assessment highlights that, according to the information available in related publication or accessible to the researcher:

- None of the assessed BID methods or tools seems fully compliant with the principles;
- The BID methods and tools assessed are partially compliant but they all seems lacking compliance with the same principles (n.11 and 12) so they cannot complement each other in order to fulfil all the principles;
- The BID methods and tools assessed could be all certainly modified to become fully compliant but the cost/benefit of this operation for each one of them is unknown.

As highlighted in section 2.3.4, cost/benefit ration is a relevant factor for a business to decide if and how to embark in a BID process. From the information above, no quantitative, neither qualitative consideration can be really extracted which could point at a direction rather than another one.
The lowest-cost option, initially appealing to any business, would be certainly consulting AskNature, which, according to several case studies reported, can support generation of bio-inspired ideas, at least in terms of the quantity of ideas. To improve other ideation metrics, it is however expected that additional research in biology would be needed. Also further research would be needed (inside and outside AskNature) to find biological analogues operating at scale and ranges of conditions similar to the problem's requirements.
Furthermore, as reported in section 2.3.4, not many experiments have been conducted which compare the effectiveness of different BID methods, especially on large number of biological analogues. Therefore, it is not certain that the cost for gathering relevant biological information and preparing functional and/or biological models in other BID ontologies (SBF and SAPPhIRE) would reduce the cost/benefit ration generated by AskNature.

Based on the considerations above, the researcher proposes a *trade-off solution* between a database like AskNature, whose abstraction of biological solution and the organization of information are not coherently structured and databases according to ontologies such as DANE or IDEA-INSPIRE which propose well structure and complex causality models.
A method and tool for organising biological information which is more complex and complete than AskNature's entries and which provide suggestion for extracted design principles of biological solutions. A method which however does not foreseen the preparation of functional/biological models according to other BID ontologies.
This method has been named *Guild-based* (or *Sectoral*) *BID method* and it is proposed as answer to Research Sub-question n.2.
The method is be described in detail in the following section 5.3 and an analysis of its compliance with the BID method's Design Principles is provided in section 5.4.

## 5.3 The Guild-Based BID method

The *Guild-Based* (or *Sectoral*) BID (GB-BID) method is named as such to emphasize the biological analogy with the Guild which represents a group of organisms carrying out a similar function within an ecosystem (see Annex 2 for the definition). As also explained in section 4.4. The transfer of this analogy is from organisms providing a similar function within the ecosystem to similar products within the market.
The GB-BID is a method which proposes to gather biological knowledge and organize it in order to build up databases (the tool). Each database contains biological solutions related to a *main function*. This is order to align also with the *sectoral* character of the EIM.
One GB-BID database to serve as a pool of organized biological information that firms from one specific industrial sector related to the main function can utilize to generate bio-inspired ideas to innovate the products/services the firms produce/provide.
A single GB-BID database has the main aim of inspiring radically new design concepts in a specific sector as well as providing bio-inspired solutions to incrementally improve existing products of that sector. Therefore, firms innovating, for instance, energy storage devices, may set up and consult a GB-BID database around the main function "store energy" where biological solutions carrying out that function are included.

The GB-BID method foresees to structure the databases according to the following *categories of information*:

- ***Biological Organism:*** The organism whose *phenotype* (*biological system* in other BID methods) carries out the main function and which is classified in the taxonomy of the biological classification. This category includes also *super-organisms*: an organism consisting of many individuals working together as a single functional unit (ex: ants colony, siphonophorae, etc.) as well as ecosystems (ex: mangrove, salt marsh, etc.) as long as the analysed function can be considered implemented at that level. Also viruses could be included in this category. Viruses do not have independent metabolism and thus they are usually not classified as organisms but they do have their own genes, and evolve by mechanisms similar to the evolutionary mechanisms of organisms.
- ***Kingdom*:** The biological kingdom the organism belongs to according to the biological taxonomy. As reference, the taxonomy of Chevalier-Smith is utilized (CAVALIER-SMITH 1998) which considers six kingdoms: Animalia, Plantae, Fungi, Chromista, Protozoa and Bacteria. This information can be relevant in order to make cross-kingdoms analysis of biological solutions.
- *(Biological)* ***Phenotype:*** Other BID methods usually refer to this category of information as "*biological system*"(Vincent et al. 2005; Helms, Vattam, and Goel 2009b). However, it is proposed to use the term "phenotype" instead. Phenotype defined as *the observable characteristic or trait of the organism* (organ, part of an organ, structure, internal process, behaviour and product of behaviour) *carrying out the function*. In fact, a complete organism itself could be considered a phenotype composed of several phenotypes. The term "phenotype" is preferred to "*biological system*" for the following reasons:
  - It comes from the domain of biology and it would help in acquainting BID practitioners to the technical language of Biology as well as facilitating dialogues with biologists;
  - it is considered more appropriate than "*biological system"* when referring to biological solutions such as biological behaviours (ex: V-formation of flying birds) and products of biological behaviours (ex: thermites mound structure and functioning).
- ***Main Function as: Main Action + Object of the Main action***:

- ***Main Action:*** It is represented by *a verb*. This definition follows TRIZ terminology for Function Statement: "*the subject* (in this case, the *phenotype*) *performs an action on an object where the action is a verb*". The main action identified in the problem definition (for instance: remove, extract, move, store etc.).
- ***Object of the Main Action*:** The entity upon which the system acts through the function. For instance referring to the functions above, objects could be: particles, molecules, fluid, etc.
- ***Object's Properties*:** Features characterizing the object upon which the system acts through the function (ex: particles of diameter ranging from 0.1-3 mm).
- ***Sub-Function as: Sub-action + objects:*** The biological solution may be a complex combination of sub-processes with their own function, object and object's properties. For instance, in the process: "to separate particles regulating flow regime", the main function + object is "to separate particles" and sub-function + object is "to regulate flow").
  Sub-functions are relevant because they can be the bridge to solve other problems not related directly to the main function. They can act as link between more GB-BID databases (see section 5.3.3) and expand the solutions space for multi-problem solving.
- ***Sub action object's properties:*** Features characterizing the object of the sub-function.
- ***Extra-function as: Extra-action + objects:*** When studying biological structures and processes, it may result that a certain phenotype (the biological solution) evolved to carry out multiple functions depending on the context within which it operates (for instance the dermal denticles of the skin of the shark can regulate drag, be oleophobic in water and prevent bacterial colonization) (Jung and Bhushan 2010; Hasan, Crawford, and Ivanova 2013). When identified, this multi-functionality can be recorded in the database as *extra-function* and be utilized, as the sub-functions, to connect with other GB-BID databases or solve other problems. This approach increases the benefit/cost ration of the process of retrieving and storing biological knowledge.
- ***Extra-action object's properties:*** Features characterizing the object of the extra-function.
- ***Biological strategy*:** This is a narrative describing *how the function is achieved* by the phenotype (Baumeister and et Al. 2011). The strategy shall contain reference to the main function and refer to the biological name of the structure/process/behavior, which allow achieving the function. For instance: "the lotus leaf stay clean because surface micro-roughness providing super-hydrophobic properties". Proving this high-level abstraction of the biological solution would allow to already extracting design principles, for instance: "self-cleaning surface by super-hydrophobicity provided by micro-roughness".
- ***Biological mechanism*:** A narrative describing *how the biological strategy works to achieve the function*. The concept of mechanism explained in detail, in biological terms. As "mechanism" in biology refers to the *causal* mechanism of a phenomenon: "*A step-by-step explanation of the mode of operation of a causal process that gives rise to a phenomenon of interest. Entities, activities, and organizational features are part of the causal mechanism for P (where P is the phenomenon of interest) if and only if they are relevant to the explanation of P*" (Nicholson 2012) Mechanisms occur on the level of structure, process, or interactions within the environmental system as a whole (Baumeister and et Al. 2011). Mechanism could be the description of geometries of a structure, of processes, of behaviours or a combination of them as long as they are relevant to explain the Biological Strategy. The description can be enriched with details such as materials, dimensions and other properties. These details, if useful, could be also repeated in other specific categories of information (such as Process Conditions).
  This category could be also represented using ontologies of other BID methods such as SBF and SAPPhIRE.
  In Engineering Design terminology, the Biological mechanism could be associated to the working structure as combination of several working principles (Pahl et al. 2007).
- ***Biological Mechanism's (*or *Process) Conditions*:** Operating conditions within which the function is carried out by the biological mechanism. This type of information may be represented by

several fields of the database depending on the process and the specific requirements the solution to the technical problem has to fulfil. For instance in case of a separation process, conditions could be: type of fluid or medium where the process operates (water, air, blood) and its properties such as Reynolds number, fluid velocity, temperature, salinity, etc. Also the source of energy available for fuelling the mechanism could be considered within this type of information.

- ***Biological Mechanism's (*****or *****Process) Attributes:*** Together with its conditions, also some attributes of the mechanism could be important to be highlighted such as the spatial scale at which it operates (by indicating the scale such as: nm, µm, mm, cm, etc.) and if it operates passively (exploiting free energy available in the environment) or actively (utilizing metabolic energy for instance).

  Both Biological Mechanism (Process) Conditions and Attributes are relevant because allow selecting, within the database, those biological solutions which may operate more closely to the requirements of the technical problem and therefore possibly inspire more relevant technical solutions. This information can also allow reflecting on difficulties in scaling up or down certain biological mechanisms and on potential for low-energy consumption technical solutions (derived from passively operating biological solution).
- ***Process Diagram/Pics*****:** A schematization of the biological mechanism through info-graphics, drawing, diagrams, photos etc. all visual information which can help in understanding the biological mechanisms beyond textual information. Efforts should be put in providing visual information as they have been identified valuable for the participation of non-technician to the ideas generation process.
- ***Environmental Conditions:*** Environmental conditions where the organism and its phenotype operate. This information can complement the ones provided by Biological Mechanism Conditions to identify specific patterns of biological solutions according to specific environmental conditions which could relate with similar environmental conditions of the technical problem. For instance biological solutions operating in seawater or desert environment, artic environment, high altitude, etc.
- ***Extracted Design Principle:*** Design principle extracted from the biology mechanism and explained in non-biological terms. This is the key information that will be used for generating ideas. Different existing methods could be used for this process and it is not in the scope of this research to elaborate on these. What it is suggested here, it is to provide already an extracted principle for each biological solution which the users could immediately utilize when consulting the database. This could facilitate the participation of non-technicians to the ideation process.

  Further principles could be extracted by the users during utilization of the tool utilizing different methodologies.

  For the purpose of this research, the extracted principles proposed for the testing and validation process have been identified by the researcher (so they are affected by subjectivity) rewriting the biological mechanisms without using biological terms but aiming at staying true to the science.

Figure 5-3 a schematic representation of the GB-BID Databse structure with its categories of information.

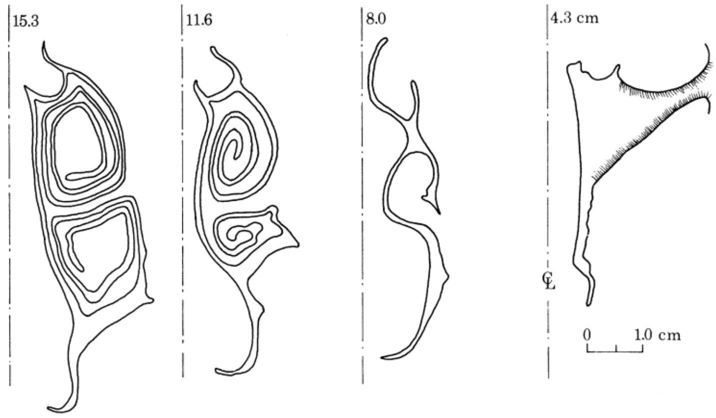
In addition, the following categories derived from the information above could be added to the database:

- ***Short description physical/working principle*****:** This should include the physical and working principles behind the mechanism and it should be described in non-biological terms. This category of information is considered useful to cluster solutions according to those principles when they are a requirement in the search for technical solutions.
- ***References*****:** List of scientific articles and other documentation utilized to extract the information to populate the entries of the database.

In general, for some categories of information, a single field in the database could be enough, for others, for instance Process Attributes and Conditions, several fields may be needed according to the specific sector tackled. This to allow multiple queries according to each one of the fields of information.
Below, in Table 5-4, an example of possible entry into a GB-BID Database:

**Ex: Camel - Respiration system**

- *Biological Organism:* Camel
- (Biological) Phenotype*:* Respiratory system – Nasal turbinates
- *Main function:* Extract moisture
- *Main Action*: Extract
- *Object of the Main action*: Moisture
- *Object's Properties*: water vapour
- *Sub-action + objects + object's properties:* Condense water vapour *(from Air)*.
- *Extra-action + objects + object's properties:* Exchange + Heat.
- *Biological strategy*: Nasal turbinates of camels extract and recover air moisture from breathing as well as exchange heat. In camels, the recovery of water caused by nasal heat exchange might reach 70 % of the potential respiratory water loss.
- *Biological mechanism*: Nasal turbinates have a 3-D convoluted spiralling structure which optimizes surface/volume ration as well as creates favourable turbulences and allow evaporating and condensate humidity. The increased surface of the nasal passageways, which possess hygroscopic property, is cooled by the inhaled air and because of evaporation (loss of latent heat), it may be cooled to below the temperature of the inhaled air. On exhalation the air that passes over the cool surface gives up heat, water condenses, and the exhaled air may even be below ambient temperature.
- *Biological Mechanism (Process) Conditions*: *Medium*: air, *Energy*: dynamic pressure gradient generated by breathing;
- *Biological Mechanism (Process) Attributes:* Passive process.
- *Process Diagram/Pics*:
  Ex: Transversal sections of the turbinates at different distances from the larynx




From (Schmidt-Nielsen, Schroter, and Shkolnik 1981)

- *Environmental Conditions:* Desert environment, high temperature excursion day-night;
- *Extracted Design Principle:* Spiralling/convoluted folded layer (with transversal section oriented perpendicularly to the direction of the fluid) which maximize surface on which fluid passes without increasing pressure losses due to increased length of obstacles to the flow.
- *Short description physical/working principle*: phase change – evaporation/condensation, hygroscopic material.

*Table 5-4: Example of possible entry in a GB-BID Database*

The GB-BID database can be utilized for both problem-driven and solution-drive approach (Figure 5-2).

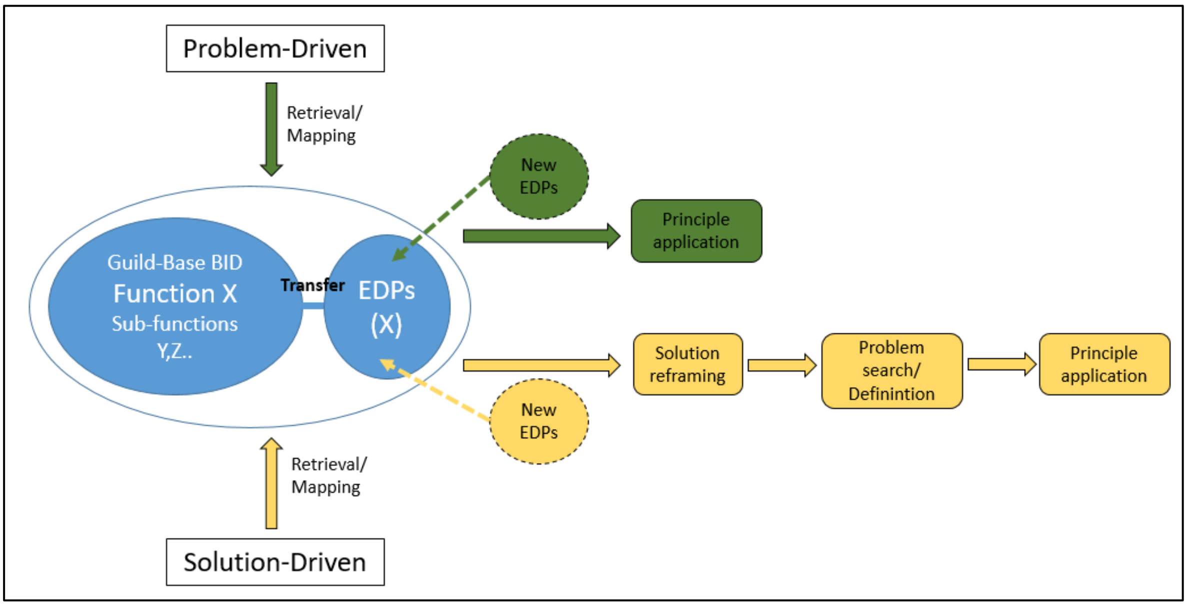



*Figure 5-2:* the GB-BID database is for both BID problem (green coloured) and solution-driven (yellow coloured) approaches. Extracted Design Principles (EDP) proposed can be considered as well as others can be extracted by the users.

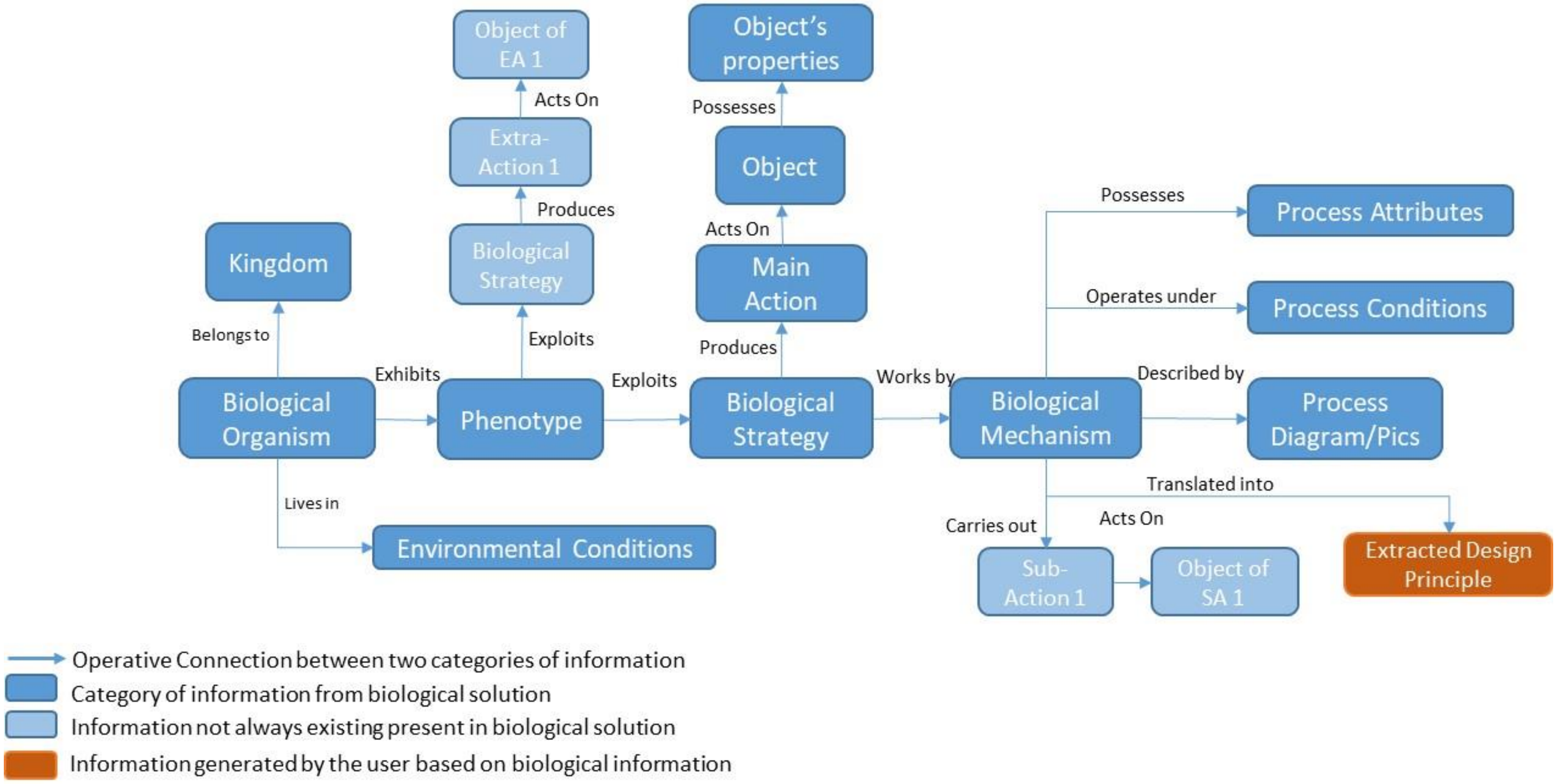



*Figure 5-3: Categories of Information of the GB-BID Database (blue boxes).Light Blue boxes are information not necessarily present in the biological solution. The arrows highlight operative connections between subsequent categories of information. The Orange box represents the extracted design principles which are generated from the biological information.*

### 5.3.1 Setting up and utilization of a GB-BID database

To set up a sectoral database and use it for generating ideas the following process (Figure 5-4) is proposed:

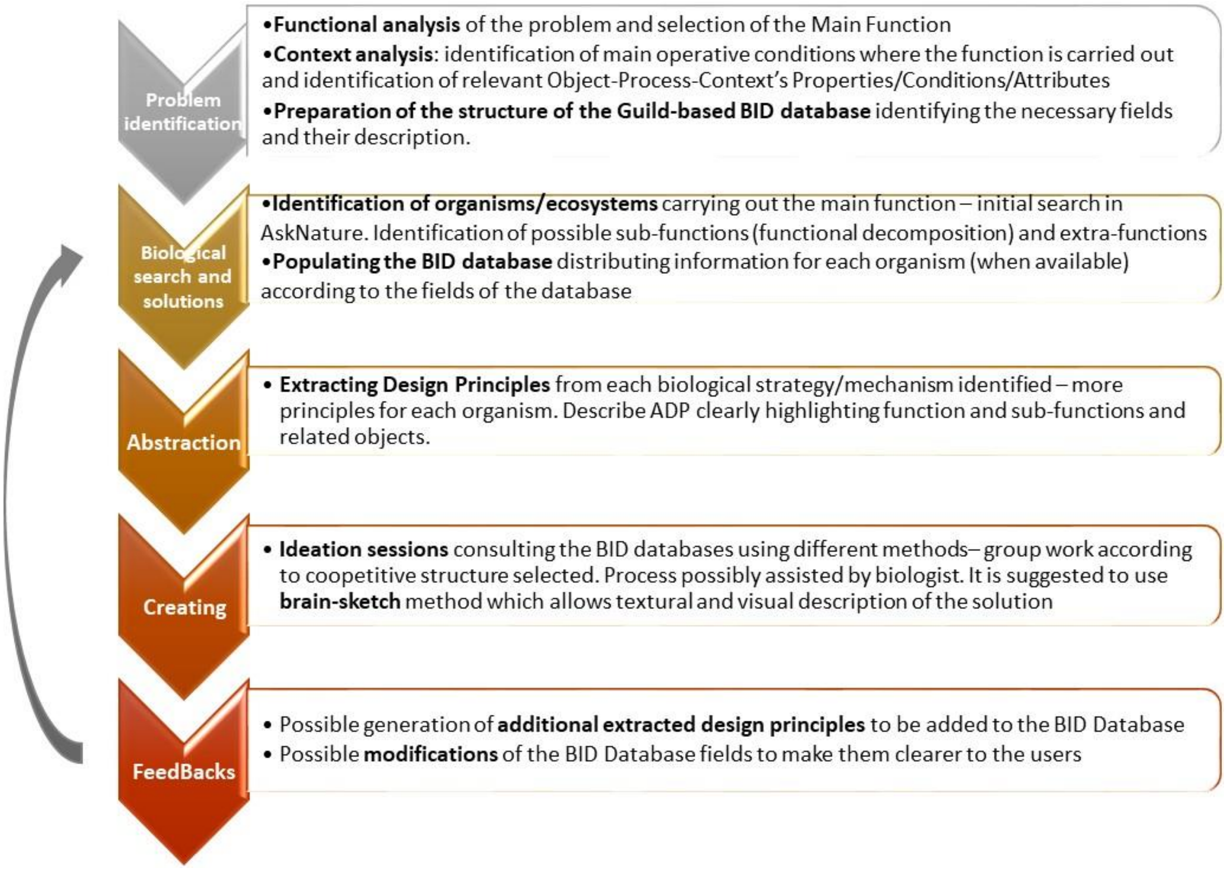



*Figure 5-4: Process for setting up a GB-BID database: The grey arrow in the scheme represents the possibility to improve/enrich the entries of the database based on feedbacks received by the users.*

#### *Biological Search*

How is the biological search conducted in order to set up the GB-BID database of a specific main function? The researcher did not develop any specific method to do this, but the following approach is proposed which has been used also to test and validate the GB-BID method (see Chapter 6).
Once the *main function* has been identified in terms of *main action* (a verb) and its object, from the "problem identification" phase (knowledge-based phase), it is proposed to proceed as follow:

1. Search into the Biomimicry Taxonomy of AskNature for that action or its synonymous;
2. Introduce those verbs into WORDNET to seek for further synonymous;
3. Review the results from WORDNET removing what is considered not relevant;
4. Check the results with the Functional Basis to see if something is missing.

This process would allow drafting a long-list of verbs compatible with both biological and engineering domains.
The search into biology can proceed starting from AskNature utilizing not only the verbs (the action) derived from the Biomimicry Taxonomy but also others which might appear in the textual part of the biological entries categorized under various groups of the Biomimicry Taxonomy. Further search into biology can be done via usual procedures such as Google searches with various keywords including the actions and consultation with biologists. Because of its sectoral nature, it may be easier to identify and involve specific experts in biology rather than generalists.

#### *Querying the Database*

The database can be consulted by using the filtering functions of MS Excel to select multiple fields. Depending on the problem to be addressed and its abstraction, a selection of records can be done in different ways. Here some examples:

- By main function (action+object): ex: *dissipate energy*;
- By main function and object's properties: ex: *dissipate thermal energy*;
- By main function and object's properties and process attribute: ex: *dissipate thermal energy passively;*
- By main function and object's properties and process attribute and condition: ex: *dissipate thermal energy passively in water;*
- By short description of mechanism: ex: *dissipate heat by increasing surface/volume ration*
- Etc.

Based on the query, the database provides a list of phenotypes whose biological strategy solves the problem. The biological mechanisms can be assessed in detail and further investigated through the provided references and eventually, if not already present, extracted design principles can be formulated.

The database can also be utilized as solution-driven approach, selecting individual organisms and deepening the knowledge of their biological strategy determining which problem it could solve.

#### *About "Robustness"*

One of the most interesting aspect of having a database with multiple entries of biological solutions for a specific main function (of interest of a specific industrial sector) organized in several categories of information, it is the possibility to determine the frequency of occurrence of similar biological strategies and/or mechanisms and/or specific features of biological mechanisms. This allows determining their weight among all the possible solutions of the database.

The frequency of occurrence above mentioned is defined as "*robustness*". The higher the frequency, the higher the robustness.

In a database populated by many biological solutions to the same problem, a higher "robustness" can indicate which are the mechanisms that evolution considered more suitable to solve that certain problem; because proposed several times and maybe in different operating conditions.

From the point of view of product innovation, it could be an indication that:

- this specific mechanism works well because it has been scrutinized not one, but several times by natural selection, in different times and places of the evolutionary process;
- it could indicate potential transferability to different contexts and even potential scalability.

Increasing the entries in the database with more organisms deploying different biological mechanisms to solve a similar problem, it would allow refining the value of *robustness* and its reliability.

For instance, if the GB-BID database for "separation" (as it is described in Chapter 8) is consulted for the following problem: "extract moisture from air" and 5 on the 30 organisms identified would utilize hygroscopic substances, then the "robustness" of using hygroscopic substances as solution to the problem would be 5/30=17%. However, a sample of only 30 organisms may not be representative of all the possible strategies for extracting moisture from air and their frequency of occurrence in nature.

The determination of frequency of occurrence of certain biological solutions is at the basis of some of the case studies (sections 8.2.1, 8.2.2 and 8.3).

### 5.3.2 Knowledge-based, Participatory nature of GB-BID

Because of its domain-driven nature (sectoral), the setup of a GB-BID Database will be a knowledge-based process where experts of a specific sector (main function of the database) will have to identify the categories of information to be stored in the databases' fields so as to be meaningful to that specific sector.

The process should be considered participatory as it can foresees the involvement of knowledge-based experts from different sectoral partners (to decide the structure of the GB-BID database) as well as working with biologists to retrieve relevant biological knowledge to fill up the fields of the database.

### 5.3.3 The scalability of the GB-BID Database

When the GB-BID method is applied to several functions and the produced databases can be utilized in synergy, a speculation around its lower cost/benefit ration may be more plausible at least in terms of quantity of ideas potentially generable.

The following scenario can describe the process of scalability of the GB-BID method (Figure 5-5):

1. Firms belonging to sector 1 decide to merge efforts and produce an initial (phase 1) GB-BID database for function 1 which they will share to generate ideas. The same database can be then expanded in more phases adding new biological entries and therefore increasing:
    a. The solutions space for ideas related to function 1;
    b. The solutions space for ideas connected to sub-functions or multi-functions that could be of interest to other firms not belonging to sector 1;
2. Firms belonging to sector 2 and 3 follow the same process as per firms of sector 1;
3. Merging together the GB-BID Databases produced by sectors 1,2 and 3:
    a. May allow finding solutions to more complex problems, combination of the main functions and/or sub-functions of the other three sectors. Ideas generated to solve more complex problems may be free of charge as the databases were already prepared independently by the three sectors
    b. May allow firms from a sector 4 to find a solutions space for their problem which could be, again a combination of main, sub-functions and/or multi-function. In this case, sector 4 could benefit of the GB-BID databases without having incurred in costs to produce it (but maybe in cost for consulting it from firms of the three sectors).

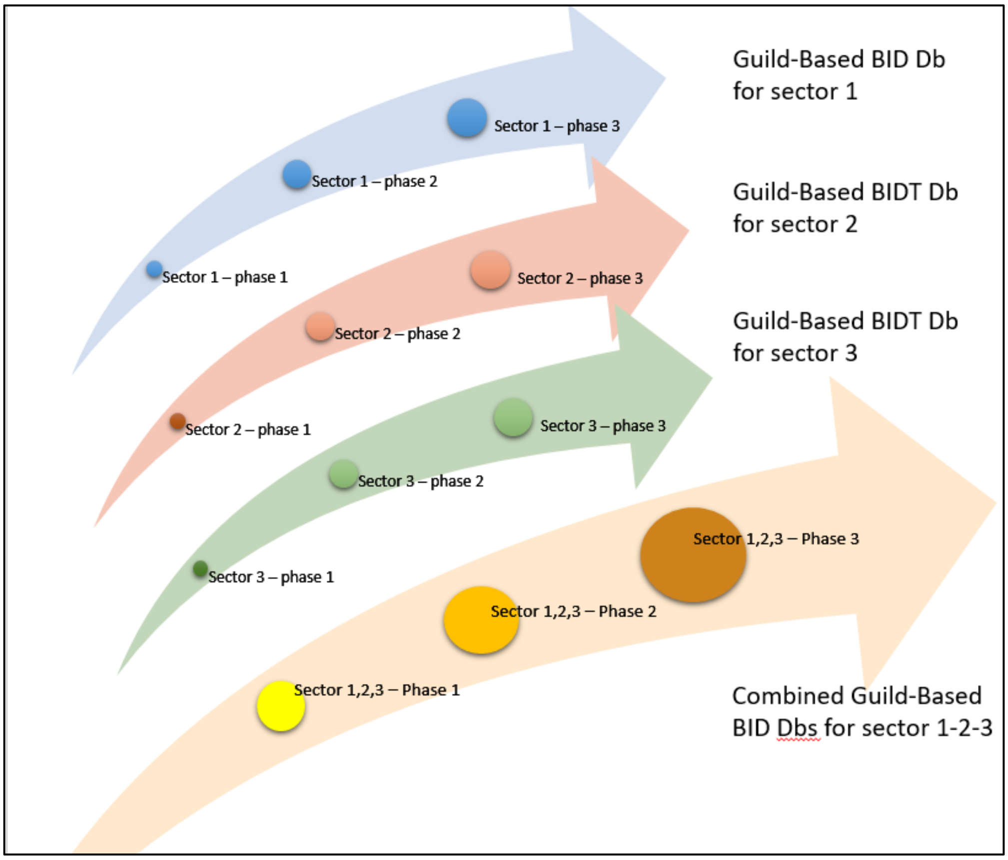


*Figure 5-5*: A diagram representing the setting up of sectoral GB-BID databases. The GB-BID databases are generated for different sectors and in different steps of expansion (represented by increasing circle along the arrow), depending on interest and resources available. Expanding one sectoral database will allow availing of more biological solutions and extracted design principles to be used for ideation (increasing size of the arrow). Using the sectoral databases in synergy will expand the solutions space for solving more complex problems than the ones related to each single database. The whole is greater than the sum of its parts.

Another way to represent the concept expressed above is presented in Figure 5-6 where each GB-BID database is represented by the main function (ex: function Z) and other sub-functions or extra-functions (ex: sub-function Y and P). Various databases may have overlapping functions (derived from sub or extra-functions). In producing more and more databases, the overlaps will increase, the need for filling up new databases will decrease and the solutions space for more complex problems will increase.

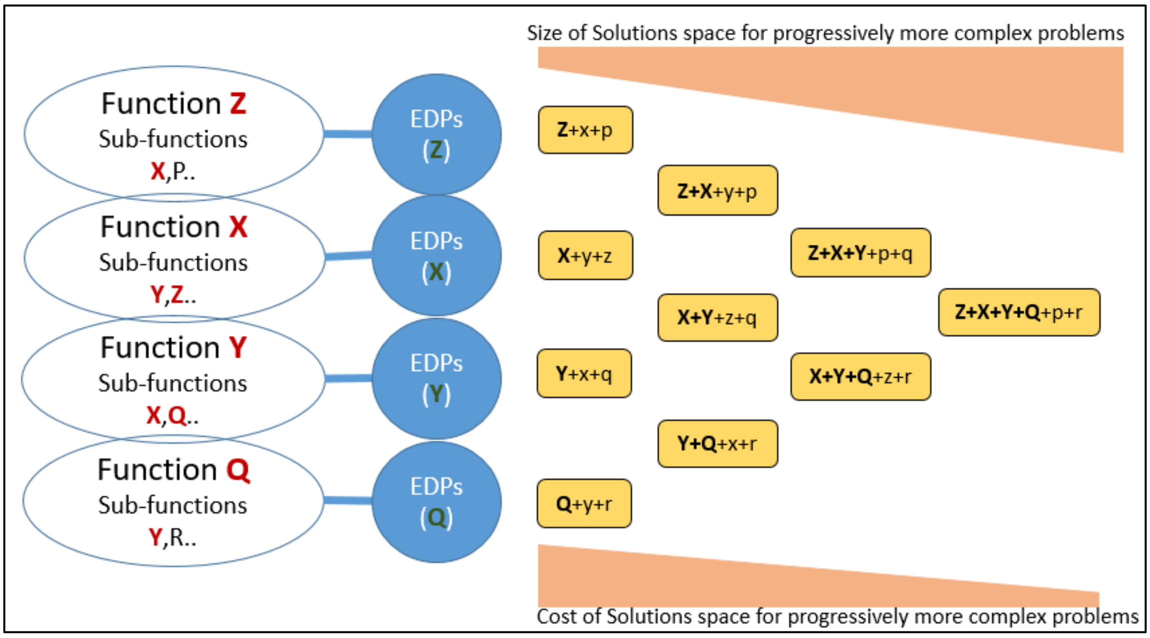



*Figure 5-6: Scalability of the GB-BID database. Database of function Z is mainly dedicated to EDPs (Extracted Design Principles) and solutions for function Z but can also generate EDPs and therefore solutions for x and p (yellow squares Z+x+p). Combining databases and EDPs of other functions and sub-functions the solution space increases (orange triangle upper part) increasing the possibility of solving more complex (multi-functional problems) while the cost for generating solutions complex problem decreases (orange triangle lower part).*

The proposed gradual scaling-up of the GB-BID database including more and more sectoral databases will eventually allow creating a biological repository of the size of AskNature but with the following advantages:

1. The biological information are selected, arranged and stored in order to be immediately useful to some agents of innovation in industrial sector;
2. There is consistency in the approach of storing contextual information which are also relevant to select appropriate biological solutions and extract design principles;
3. Because of the growing amount and type of biological entries, the "robustness" of biological solutions will be determined with higher accuracy and granularity. This would contribute to increase the confidence in using robust biological solutions as analogy.

## 5.4 How the Guild-based BID method comply with the extracted principles

In order to confirm the compliance of the GB-BID method with the BID methods' Design Principles identified in Table 5-2, the following Table 5-5 provides an analysis on each of the thirteen principles:

| BID methods' Design Principles | GB-BID compliance |
|---|---|
| 1. Allow Building up and replenish a repository of knowledge for Ideas | The GB-BID is a structured database with fields of categorized information and can be expanded according to the needs. |
| 2. Useful to specific Business guilds - Sectors | The GB-BID is sectoral and therefore is conceived for the participation of business guilds. |
| 3. Introduce mixed modalities in representation including visual and textual one | Both textual and multi-visual representations are considered (drawings, diagrams of biological mechanisms, photos). |
| 4. Engage experts in the domain of the problem in the ideation process | The GB-BID method is specifically conceived for knowledge-based experts. They are the ones who frame the problems and are interested in finding bio-inspired solutions. |
| 5. Provide both generalized and detailed description of the biological phenomena | The GB-BID database provides distinction between biological strategy and more detailed mechanism as well as contextual information and short description of mechanism (the physical and working principles). |
| 6. Present diverse stimuli linked to shared principles (multiple analogues) | The number of entries in the GB-BID database allows identifying similar principles coming from different organisms and strategies. Also, the frequency of occurrence of similar biological solutions can indicate evolutionary "robustness" and be preferred for analogical transfer. |
| 7. Incorporate structures of categories of information | The GB-BID is a structured database with fields of categorized information. |
| 8. Be expandable in biological entries for addressing specific problems (automated or not) | The GB-BID databases are expandable with new entries. Furthermore, the GB-BID method already foreseen the introduction of sub and extra functions describing the biological mechanisms. This allows already querying one sectoral database for different problems than the one related to the "main function." |
| 9. Allow for both problem and solution driven approach | The GB-BID database can be utilized for both approaches |
| 10. Facilitate access of managers to ideation process to shape ideas embedding their knowledge of the overall innovation process and acknowledging them | The GB-BID databases is conceived to incorporate the BID process of ideation within a firm (or group of firms) so that participation to the process is allowed and facilitated also for non-technical people coming from different departments and background. |
| 11. Provide extracted principles | One extracted principle is already provided by the GB-DIB database to facilitate the ideation process and allow non-technician to participate to the process. |
| 12. Embed biological information of function's object and context which can relate with problem's context and requirements | The GB-BID database structure and its categories of information is conceived to respond to this principle by creating fields where such type of information can be stored |
| 13. Provide multiple biological analogues to increase chance of finding technically scalable biological mechanisms | The GB-BID method already foreseen the introduction of sub and extra functions describing the biological mechanisms. This allows already querying one sectoral database for different problems than the one related to the "main function." |

*Table 5-5: Analysis of compliance of the GB-BID method with the BID methods' Design Principles*

### 5.4.1 Considerations on the cost/benefit ration of a single GB-BID Database

Setting up a single GB-BID database for a specific sector has a cost which is directly proportional to the number of entries. Not all the entries will cost the same, depending on the effort occurred to retrieve the information and store it in a meaningful way in the database.
In terms of cost/benefit ration however the following qualitative considerations can be done comparing, for instance, the sectoral/function approach of the GB-BID with AskNature, which is the only similar database accessible and also upgradable from external entities.
Introducing a biological entry in AskNature has a lower cost than an entry in the GB-BID due to less effort in retrieving and storing information. In particular:

- Information in AskNature are not distributed in fields but stored in bulk without any specific structure;
- If there is identification of the main function of the biological strategy, there is no clear indication of possible sub-functions;
- There is no consistency in the depth of information provided. Some entries are just single statements extracted from nature documentaries without any scientific reference or clear explanation of strategy and mechanisms. Identification of "robustness" of biological mechanisms such as in the GB-BID database it is not done;
- Entries in AskNature are not planned and they are prepared mainly on a voluntary basis, not necessarily by biologists and without any specific purpose. Before being published however the entries are checked by biologists for accuracy;
- AskNature is sustained by grants received from entities which are not using AskNature but share the vision of promoting biomimicry to the public. Therefore, less attention is given to cost/benefit ration of producing innovative products.

However, if we look at the benefits side, AskNature may have disadvantages compared to the GB-BID method especially when considering the purpose of a BID method which should be to generate bio-inspired ideas more likely to become innovation:

- In AskNature the information provided in each biological entries are often not detailed enough to extract useful design principles (no information on context, operating conditions and details of the object of the function);
- The Biomimicry Taxonomy upon which AskNature is structured, it is organized according to biological functions which do not find necessarily correspondent in technical functions (from this the need to utilized an intermediary tool - for instance the engineering-to-biology thesaurus to bridge between the two domains). Therefore queries with functions as keywords may provide partial or even deviating results;
- The description of the biological mechanisms do not put emphasis on sub-functions therefore they cannot the utilized as analogy for solving problems different from the main function;
- Extra-functionality of biological systems is not highlighted. For instance, AskNature provides two independent not-linked entries for the same biological structure which can provide two functions (ex: toucan beak dissipates heat and resist to impacts has two distinct entries).

Measuring the difference of cost/benefit ration between AskNature and GB-BID (as well as with other BID methods) is not easy. There are no statistics around innovative products (at least ideas which went beyond the design concept phase) derived uniquely from the consultation of AskNature. The same is valid for other BID methods which could be used for comparison (ex: SBF-DANE and IDEA –INSPIRE) and for which the cost for organizing the biological knowledge, due to the proposed complexity of the representation of the biological model, is higher than AskNature.
In this research, an attempt has been made to carry out at least a qualitative assessment among GB-BID, AskNature and SBF-DANE through the ideation workshops (see Chapter 7).

# PART 3

# TESTING AND VALIDATION

# 6. TESTING AND VALIDATION – tool preparation

This phase foresees the testing of the Guild-Base BID method in order to confirm it as a valid answer to Research Sub-question n.2. To do this, a Refined Research Question needs to be explored:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

The methodological approach has been described in section 3.3.
The first step of the approach it is to select a specific sector (related to a specific function). For this research the sector of **Separation Technology** and the main function "***To Separate***" have been selected. In this case the "main function" coincides with the "main action" in the GB-BID method. This was decided in order to broaden the range of biological solutions which could populate the GB-BID Database on Separation and the potential for producing meaningful case studies.

## 6.1 Separation Technology Sector - Why

In order to test the proposed Evolutionary Innovation model and the Guild-based BID method, a specific "function" or "sector" analogous to a biological guild had to be selected. The researcher opted to select the sector of Separation Technology and "to separate" as the main function.

Why was this sector selected? Filtration/separation technology is everywhere in modern industrialized countries, and is rapidly being applied in developing countries as well. As a global business segment approaching $85 billion in annual revenues, Separation Technology sector stays below the average consumer's radar because the product that they generally purchase is not a filter (Ramsey 2017).
What consumers buy are beverages that has been filtered, cars that contain filters, fly in planes whose jet fuel, hydraulic fluids and cabin air have been filtered. Modern industries that are made possible, at least in part, by filtration and separation technology include: water treatment, automotive, aerospace, chemicals, pharmaceuticals and diagnostics, etc. (see Table 6-1: for an extensive list of industries)
In charts below the global filter use by region and category (Ramsey 2017).

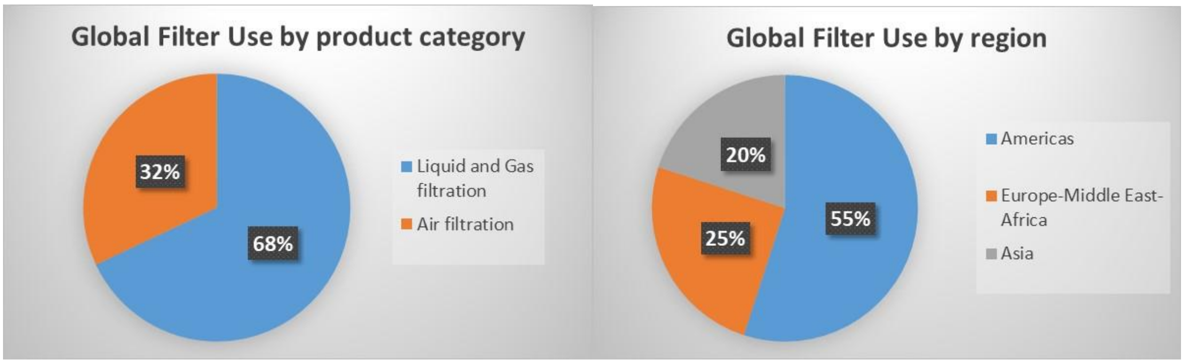



*Figure 6-1: Global filter use by product category and by Region (Ramsey 2017).*

*Table 6-1: Diverse Market Segments within Major Markets(Ramsey 2017): n.b. there is no relation among rows of the table*

| **Water/ Wastewater 42%** | **Industrial Process 20%** | **Transport 13%** | **Life Science 13%** | **HVAC/Pollution Control 12%** | **Original Equipment Manufacturer Applications** |
|---|---|---|---|---|---|
| Municipal Water/ Wastewater<br>• Particulate | Chemical Processing<br>• Particle filtration | Automotive | Pharmaceutical/Biotech Manufacturing | Residential HVAC<br>• Particle filters<br>• Biological | Consumer Electronics Vents and Filters |

| | | | | | |
|---|---|---|---|---|---|
| • Biological<br>• Desalination<br>• Aeration<br>• Solids digestion<br>• Odour Control | • Catalyst support<br>• Coalescing<br>• Vents<br>• Pollution control | • Fuel- Oil- Air- Cabin Air- Sensor<br>• Motor<br>• Lamp vents | • Particulate and biological filters<br>• Water supply<br>• Raw materials<br>• Vent filters for tanks | and aerosol filters<br>• Odour control | • Controlled venting and heat dissipation<br>• Dust and liquid protection<br>• Adsorption of corrosive gases |
| Consumer/ Commercial Water<br>• Point of use and point of entry filters for hardness<br>• Taste<br>• Biological purity | Oil and Gas<br>• Particle Removal<br>• Oil/Water separations<br>• Chemical recycling | Heavy Vehicle/ Off Road<br>• Fuel- Oil- Air- Cabin Air- Sensor<br>• Motor<br>• Lamp vents | Laboratory Filters<br>• Liquid and Gas filters of various types for small scale testing and process development | Commercial HVAC<br>• Particle and biological filters<br>• Adsorption of toxic and corrosive gases<br>• Odour control | Industrial and automotive sensor vents<br>• Controlled venting and heat dissipation<br>• Dust and liquid protection,<br>• Adsorption of corrosive gases |
| Industrial Water/ Wastewater<br>• Make-up water and rinse water for manufacturing process<br>• Removal of heavy metals and chemical contamination | Fluid Power<br>• Particle removal<br>• Oil/Water separation | Aviation/Aerospace/Military<br>• Intake Air- Oil- Fuel- Cabin Air- Hydraulic | Medical Devices<br>• Particle<br>• Bacteria<br>• Virus removal from fluids and vents | Medical and Industrial Controlled Environments<br>• Infection control<br>• Isolation and containment of particulates<br>• Biologicals<br>• Aerosols using filters<br>• Chemicals and UV | Wicking media for Air fresheners and writing Instruments<br>• Porous media for controlled rate fluid transfer and release |
| | Microelectronics<br>• Particulate removal<br>• Chemical and rinse water purity<br>• Exotic gas purity | | In-Vitro Diagnostics/ PCR Testing<br>• Particle and Biological Filters<br>• Fluid/Capillary Transfer | Industrial Pollution and Exhaust Gas Control<br>• Particulate and Toxic Gas Removal<br>• Flue Gas Desulphuriz.<br>• Carbon sequestration<br>• Mercury absorption | Medical Device and Diagnostic Vents and Wicks<br>• Sample fluid or reagent transfer<br>• Controlled Venting |
| | Pulp and Paper<br>• Coarse slurry separators<br>• Slurry dewatering screens<br>• Particulate filters for hydraulics and pneumatics | | Food and Beverage<br>• Particle and biological filters for visual clarity and biological safety<br>• Vent filters for tanks | | |
| | Power Generation<br>• Particulate filters for fooling and processing water<br>• Pollution control filter media for particulates and gases | | | | |

The following trends are driving innovation in separation technologies (Ramsey 2017; Sutherland 2013):

- *Population growth and rapid urbanization* will increase demand, which will require increased production and increases in manufacturing efficiency and infrastructure.
- *Digital technology* has been improving for decades and trends call for this to continue. Smaller and more sophisticated computer circuits will require advanced filtration systems.

- *Natural resource scarcity and climate change* will make it increasingly difficult to supply an ever-growing population with clean water. This will increase the use of desalination technologies, and recycle and reuse of wastewater on a consumer, commercial and industrial scale.
- *Transformative advances in healthcare* with advances in diagnostic and drug therapies and an increased focus on a cleaner environment, which utilize filtration and separation rather than chemical technologies to make products safer.
- *The race to zero emissions and zero discharge* for industrial manufacturing, public utilities, automotive and aerospace will be a technology challenge on many fronts. Filtration and separation are among the major enabling technologies for this purify, recycle and reuse process.

The above trends generate the following driving forces on the separation technology sector:

- *Request for Finer Filtration:* Automotive engines and transmissions, turbines and compressors are built with more sophisticated machine tools requiring closer tolerances. Pharmaceuticals and food/beverages producers are faced with increasing bacteria and virus removal challenges. Semiconductors (microelectronics) have finer minimum circuit/feature sizes that are now in the nanometre range.
- *Filtration Media Specialization:* Virtually every filter or filtration process/system requires a filtration medium made from any number of materials of construction including metals, plastic polymers, ceramics, natural grown substances, such as walnut shells, wood pulp rice hulls, along with mined ores and minerals.
- *Request of Re-usable filters:* The filtration industry has long been a disposable market and yet reusable filters, able to be cleaned in-situ or extended-life filters with greater contaminate holding capacity are rapidly growing in popularity and use.
- *Global Manufacturing & Supply:* Customers seek the latest filtration media, filters and filtration and separation systems wherever they can locate them as they strive to use the best available technology wherever it is found and at the lowest cost. It is quite common for filtration and separation technology suppliers to follow their customer overseas, building or buying nearby production facilities.
- *Regulation/Legislation requiring Pollution Prevention/Control:* Legislation and regulation have had a significant impact on increased growth within the filtration industry, with little expected change or slowdown in sight. This has driven the ongoing need for filtration and separation technology to ensure or remediate a cleaner environment.

Most of the driving forces described above have been at work in the marketplace for many years. The impact on the filtration industry, over the past 50 years, has been a succession of developments intended to improve process efficiencies and economics (Sutherland 2013). These have included:

- expansion of the use of organic, polymeric membranes in the whole range of filtration equipment;
- acceptance of an increasing range of organic polymers as efficient filter media;
- development of inorganic membranes, especially ceramics;
- spread of cross-flow (thin layer) filtration, as a means of operating membrane processes with reduced fouling;
- availability of membranes able to operate in the ultrafiltration, microfiltration and nano-filtration ranges, as well as their original use in reverse osmosis;
- development of surface treating processes, such as thermal bonding or coating, able to modify the filtration performance of a woven or felted material;
- development of spun-melt (extruded filament) fibrous media, progressively as spun bonded, melt blown, flash spun, and, most recently, electro-spun materials;
- the use of multi-layer composite media, enabling the production of strong media with a good filtration performance;
- the production of multi-component fibres, to give a range of fibre properties;

- the preparation of combination media, able not only to filter, but also to remove odour or colour, or to kill bacteria.

## 6.2 Separation Technology Sector – What

Once the sector has been selected, two main dimensions need to be investigated:

1. The products generated by the sector and their design parameters. This allows to set up the related Guild-based BID database;
2. The structure of the sector. This allows to frame the related Evolutionary Innovation Model;
3. Biomimetic research and products;

### 6.2.1 Separation processes and device

Because of its applicability, separation technology deploys a vast range of devices. An assessment of the devices has been carried out consulting Filtration and Separation Manuals (ex: (Sutherland 2008)), scientific and non-scientific literature on the subject as well as through dedicated commercial and training courses materials (the researcher attended a short-course on solid and liquid separation at the Filtech Conference-Exposition 2018 (Anlauf 2018)). It has to be highlighted that despite the importance of the sector, the researcher could not find any coherent and comprehensive study reporting on the "universe" of separation technology. Therefore, the researcher believes that the assessment hereby carried out as a value in itself beyond the scope of the research.
Annex 3 provides a summary of the main separation devices identified according to different parameters. Below, in Table 6-2, and extract from the Annex. The colour code refers to the separation type: liquid-liquid, gas-liquid, liquid-solid etc.

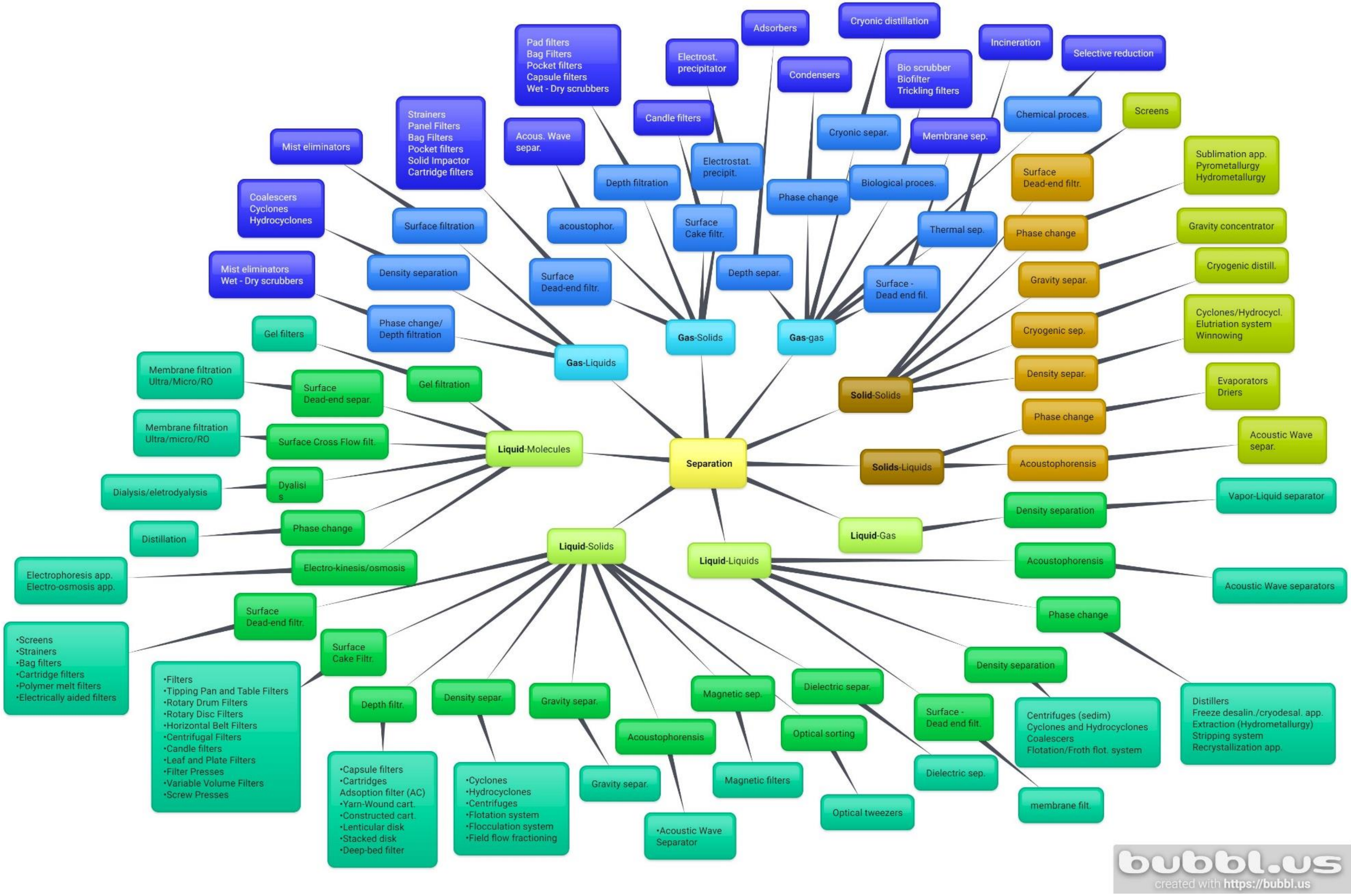
| Technology name | Separation Principle | Driving force | Process/Strategy | Function | Continuous/ Discontin | Type of separation |
|---|---|---|---|---|---|---|
| **Coalescers** | Density Separation enhanced by coalescence and electric field | Gravity, Surface energy, Van der Waal forces Electric field | Separation via coalescence by interception and hydrophobicity/phillicity or by electric fields (dehydration and desalting) | Separate two Liquids or Liquid from gas | Contin/discont | Gas-Liquids |
| **Wet and Dry Scrubbers** | Depth filtration assisted by chemical reactions and ab-adsorption | Hydraulic pressure Absorption Adsorption (surface energy) | Chemical reaction and or Depth filtration (absorption/adsorption) | Separate (and recover) liquid or solids from gas streams | discont | Gas-Solids |
| **Vapor-Liquid separator** | Density Separation - Vapor-Liquid Separation | Vapour/Heat | Separation of gas from liquid via pressure reduction | Separate gas from liquid | Conti/discont | Liquid-Gas |
| **Centrifuges (sedim)** | Density Separation - Sedimentation by centrifugation | Centrifugal force | Sedimentation/Liquids Separation via centrifugal force | Separate two liquids/ Separate solids from liquid. Clarification | contin/discont | Liquid-Liquids |
| **Membrane filtration Systems** | Surface - Dead-End Filtration Surface - Cross-Flow Filtration | Hydraulic pressure Chemical Potential Osmotic potential | Liquid cross-flow, dead-end surface filtration via pressure/Reverse/forward Osmosis. Micro, Ultra, Nano filtration, dynamic cross flow filtration | Separate solids/molecules from liquid. | contin/discont | Liquid-Molecules |

| Technology name | Separation Principle | Driving force | Process/Strategy | Function | Continuous/ Discontin | Type of separation |
|---|---|---|---|---|---|---|
| **Bag Filters** | Surface - Dead-end Filtration<br>Depth Filtration | Gas pressure<br>Hydraulic pressure | Liquid and gas Surface/Depth filtration depending on media. Also some cake formation | Separate (and recover) solids from liquid and air/gas. | discont | Liquid-Solids |
| **Acoustic Wave separators (acoustophoresis)** | Acoustophoresis | Acoustic pressure | Separation by orthokinetics via acoustic waves | Separate solids or liquid from liquid or gas stream | Contin/discont | Solids-Liquids |
| **Screens** | Surface - Dead-end Filtration | Hydrostatic pressure | Liquid/air Surface filtration via meshed surfaces | Separate solids from liquid of different viscosity or separating mixtures of solids | Contin/discont | Solids-Solids |

*Table 6-2: Example of extracted information from Annex 3. The colour code refers to the separation type: liquid-liquid, gas-liquid, liquid-solid, etc.*

From the summary table of Annex 3, two maps have been extracted. The first one (Figure 6-2) maps the overall "universe" of separation technologies from the point of view of the separation type. For each type of separation (liquid-liquid, gas-liquid, etc.) the various separation processes and the technologies/device utilized have been mapped. The second one (Figure 6-3) maps the different separation processes and for which type of separation they are utilized. This map in particular is utilized to compare it with separation processes occurring in nature (see Chapter 8).

*Figure 6-2: Map of the "universe" of separation technologies from the perspective of the type of separation. Different colours within the red circle represent different main medium of separation processes (Gas, Liquid, Solid). Increasing darkness of same colours represent shift from type of separation, to separation principle to separation technology.*



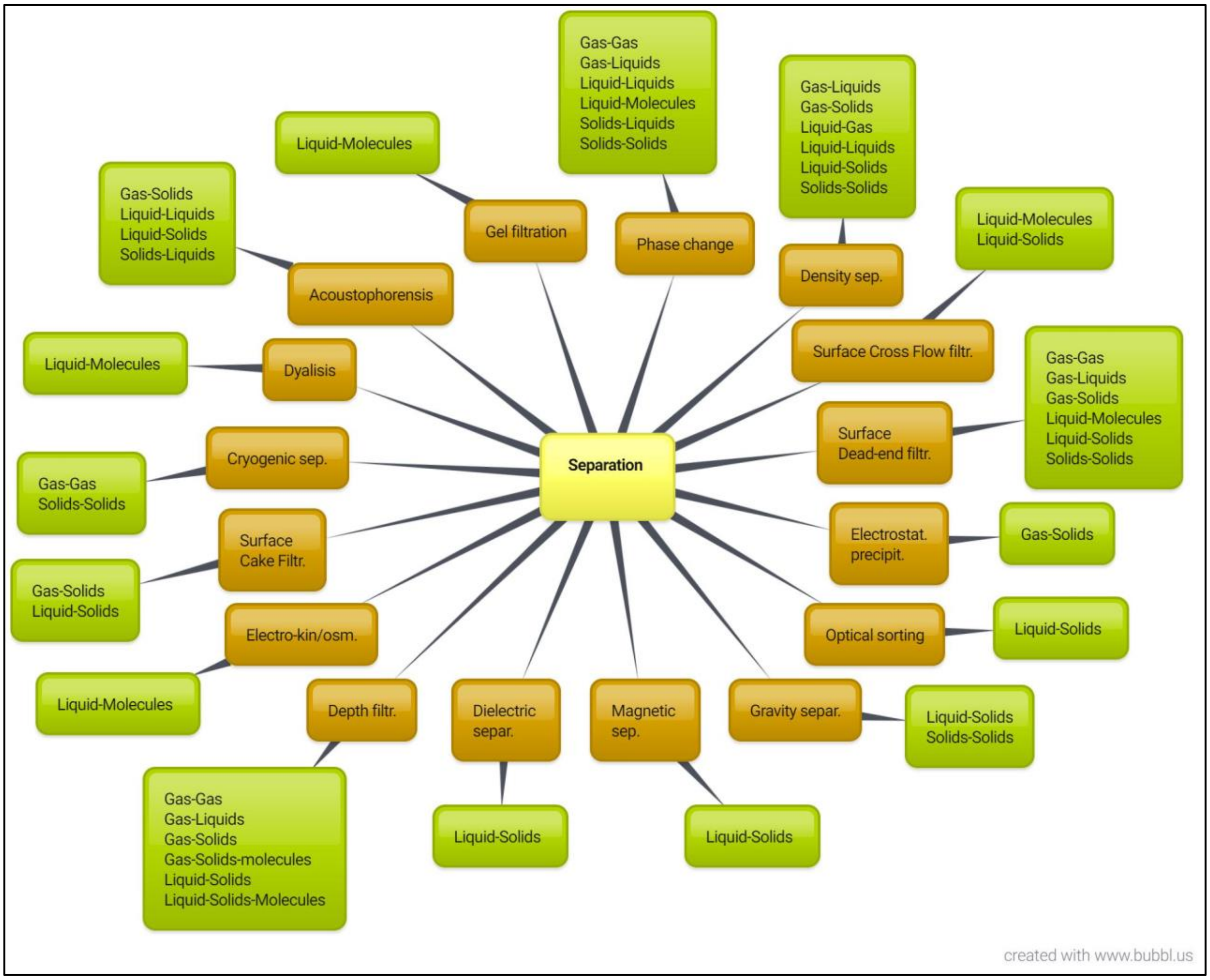



*Figure 6-3: Map of different separation processes and for which type of separation they are utilized. Orange colour: different type of separation principles. Green colour: type of separation process carried out with separation principles.*

### 6.2.2 Decisional criteria based on the context

Which are the main criteria for selecting and start designing a separation device? From the assessment of Annex 3 and the maps provided above, the following criteria have been identified:

**Type of separation needed -** the following have been identified:

- Liquid-Solids (for instance removing particles from liquid medium)
- Liquid-Liquids (for instance separating liquids of different density/viscosity)
- Liquid-Molecules (for instance removing molecules from liquid medium)
- Gas-Liquids (for instance removing aerosol from gaseous medium)
- Gas-Solids (for instance removing particles from air)
- Gas-Gas (for instance separating gasses of different chemical composition)
- Solid-Liquids (for instance removing liquids from solid medium)
- Solid-Gas (for instance removing gasses from solid medium)
- Solid-Solids (for instance separating solids of different density/other properties)

**Characteristics of the medium** from which something needs to be separated:
- *Flow Velocity;*
- *Flow Rate;*
- *Reynolds number*: it is the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities. This relative movement generates fluid friction, which is a factor in developing turbulent flow. Counteracting this effect is the viscosity of the fluid, which tends to inhibit turbulence. The Reynolds number quantifies the relative importance of these two types of forces for given flow conditions, and is a guide to when turbulent flow will occur in a particular situation. At low Reynolds numbers, flows tend to be dominated by laminar (sheet-like) flow, while at high Reynolds numbers turbulence results from differences in the fluid's speed and direction, which may sometimes intersect or even move counter to the overall direction of the flow.

**Characteristics of the retentate** (what needs to be separated from the main medium) - particles, gas, liquid such as:
- Type of material, Dimensions, Shape, Density, Chemical properties, Physical properties, Electrical properties, Bulk materials characteristics and behaviour.

### 6.2.3 The Structure of the Separation Technology Sector

The vast majority of separation device can be decomposed into two main elements: the separation/filtering medium/element (for instance, membranes, grids, granules, etc.) and the "other-than-the-medium/element" which represent the ancillary parts thanks to which the separation process carried out by the medium/element can be achieved (for instance, cases of membranes, piping, tanks, etc.).
Describe the production process of each separation device is not relevant for this stage of the research. Nevertheless, for the separating medium/elements, five main stages of the industrial process can be largely identified which are carried out by different types of firm (Sutherland 2008). These stages are:
1. Making of the basic material from which the separation medium/element is to be made: a metal wire, a natural or synthetic fibre, a ceramic powder, an extruded plastic filament, and so on;
2. Conversion of some of these basic materials into a form in which they can be used to make separation media/elements: the spinning of fibres or the twisting of filaments into a yarn, the crimping of a wire, etc.;
3. Formation of the bulk separation media/elements: the weaving of a cloth or monofilament mesh, the moulding and sintering of a mass of plastic or metal fibre or powder, the production of paper, the preparation and processing of a sheet of membrane (all together with any necessary finishing processes);
4. Conversion of the bulk separation media/elements material into pieces of the particular size and shape required for the medium to fit the filter, which may include, for example, the pleating of flat material;
5. Making of the separation device itself, including the fitting or adapting of the separation media/elements to its position in the filter. Sale of filters to Original Equipment Manufacturers or/and end-users of different sectors (Municipal, industrial water/ waste water, automotive, aviation, industrial chemical processes, energy sector…).

These five stages of the preparation of the separating media/elements are represented in Figure 6-4 aligned with the preparation of the "other-than-separation media/element" parts, this one represented into three stages, and connecting with the sequence of production of the separation media/element at different stages:

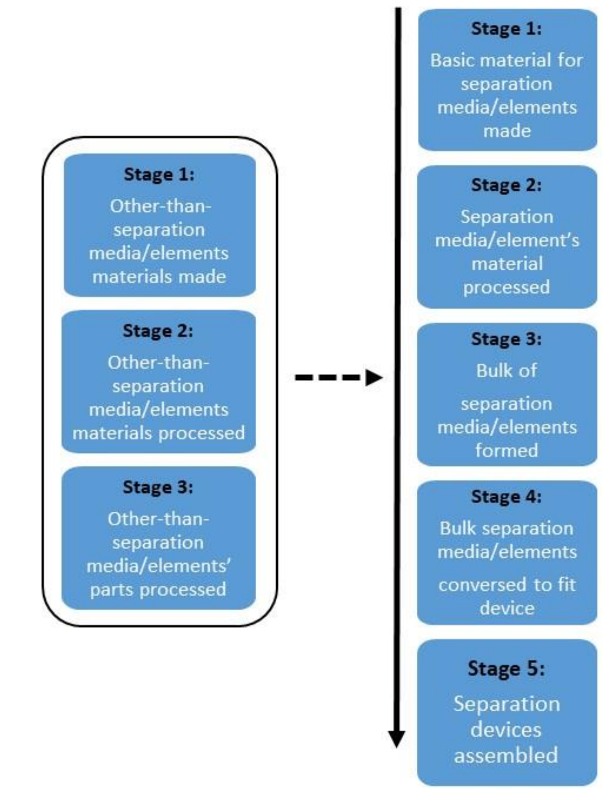



*Figure 6-4: The main stages of the industrial process in the Separation Technology sector. Continuous black arrow indicates the progress of production of the separation device along five stages; from production of basic material for separation media to the assembly of the separation device. Connected to this process (dashed arrow), the production of "other-than-separation-media" materials and parts. All will contribute to the final assembly of the separation devise of stage 5.*

The sector therefore shows a multi-tiers supply chain from Tier 3 to Tier 1, where Tier 3 suppliers are the foundation of the entire supply chain. They provide the required materials, such as metals and plastic (for the filter media and other parts of the separation device), in their raw form or almost raw state to Tier 2 and Tier 1 companies. Tier 2 refers to companies that produce and supply parts from the material obtained via Tier 3 to Tier 1 level. Tier 1 companies, are the firms which have a direct relationship with and sell separation devices to Original Equipment Manufacturers (OEM) which assemble in other devices (ex: cars in automotive sector) and sell them under their own brand name and warranty.

### *Innovation process in the sector - a very brief assessment*

The researcher participated to the Conference/Expo Filtech 2019. Filtech is the largest events dedicated to the Separation Technology sector Worldwide. The conference is a globally acknowledged platform for scientific exchange of the latest research results and knowledge transfer between theory and practice in the separation sector. More than 200 papers from 35 countries are presented. At the exposition, more than 400 companies present their cutting-edge products and innovations for the chemical industry, as food & beverage, life science, minerals processing, pulp & paper, waste management, water treatment, environmental engineering petrochemicals and many others.

During the event the researcher interviewed 28 firms mainly from EU countries (2 from USA) asking questions related to their internal process of innovation. The companies were 14 from TIER 1 level (producers and sellers of separation technologies) with net sales up to >3000 M euros and 14 from TIER 2 level (production of filtering media or other elements of filtering devices) with net sales <100 M Euros. Representatives have been interviewed for 5-10 minutes asking them the following questions:

- *Is your R&D process internal, external (cooperating with Universities, or companies of the supply chain) or mixed?*

- *What drives your innovation? Technology push/Demand-pull?*
- *Do you aim at incremental or radical innovation, or both?*
- *Do/did you cooperate with competitors? If yes, in which phase of the innovation process*

The results, also shown also in Figure 6-5, highlight that R&D is mainly carried out internally (two cases of coopetition but only for the commercialization aspect of the product), the innovation process is client driven (demand-pull) and innovation is mainly incremental (only two cases of radical one identified).

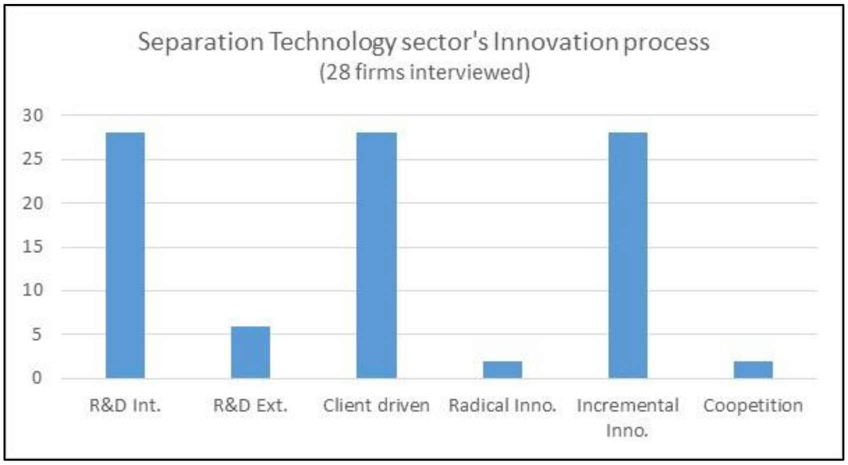



*Figure 6-5: Characteristic of the innovation process in Separation Technology sector.*

Despite the small sample of interviews, this assessment provides an indication on how Open Innovation models and Coopetition are not yet utilized within this sector which seems following more traditional innovation models with R&D conducted mainly internally, to develop incremental innovation and driven by clients.

### *Bio-inspiration in the Separation Technology Sector*

Currently many researches are on-going around bio-inspired separation processes, however reviews on already existing bio-inspired solutions on the separation technology market could not be found.

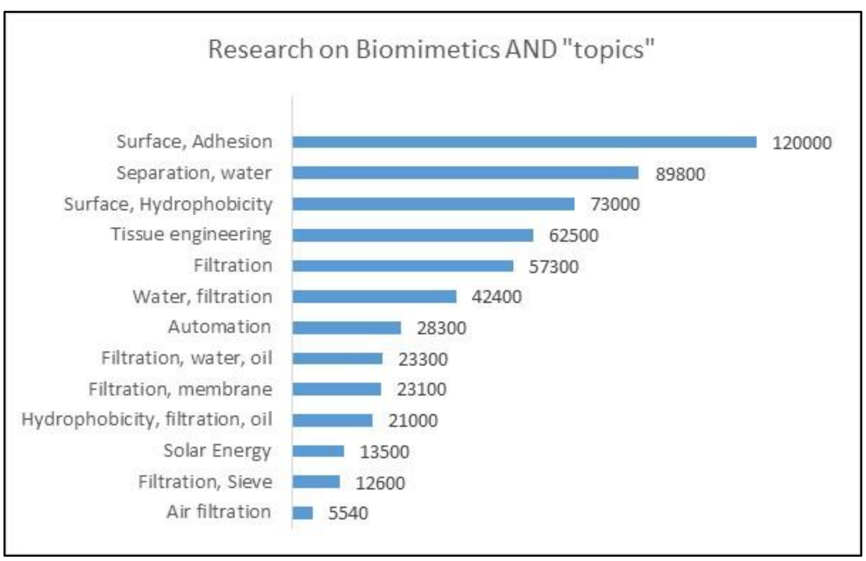



*Figure 6-6: Google scholar search for "biomimetics" AND "term" AND "other term" (including patents).*

A search in Google Scholar was carried out in September 2019 using as keywords "biomimetics" AND other thematic words related to separation technology but not only (ex: automation, solar energy, tribology) (see Figure 6-6). This to provide an indication about the interest in biomimetics research and how the separation technology sector is positioned. Bio-inspired functional surfaces results as the most explored biomimetic aspect, because of the potential for solving multi-domain problems (for instance in tribology, medicine, textile industry to mention a few) and already a robust knowledge about shapes and behaviours of textured surfaces. For the separation technology sector, the research around functional surfaces is mainly for applications to membranes and sieves for desalination and water-oil separation.

The above information related to the Separation Technology sector confirms that the sector can be indeed an interesting case study for this research because:

- The multi-staged structure with a mix of Tier 1, 2 and 3 companies and Open/Coopetitive models of innovation seem not applied yet. These are interesting conditions to try applying the principles upon which the Evolutionary Innovation Model is based.
- Biomimetic research is mainly addressing filter media but neglecting other aspects of a separation process or device leaving space for more bio-inspired innovation through BID.

## 6.3 The Guild-based BID Database for Separation

Based on the parameters identified in section 6.2 a GB-BID database for the function "to separate" is proposed with the following fields:

| Field in the database | Description |
|---|---|
| **N** | The number of the biological entry |
| **AskNature** | Signal if this system is also present in AskNature (Y/N) |
| **Kingdom** | As per description in section 5.3.1 |
| **Biological - Organism** | As per description in section 5.3.1 |
| **Phenotype** | As per description in section 5.3.1 |
| **Main Action** | As per description in section 5.3.1 |
| **Main Object - What is Separated** | Description of what needs to be separated from the main medium. (the *retentate* in case of filtration). Ex: particles (from water) |
| **Medium** | *Process Condition*: The medium (fluid) where the function is carried out: water, air, blood, mucus, etc.. |
| **Information about the separated** | *Object Property*: Additional information about the elements separated. Size/density/density variability/materials, etc. (ex: particles of diameter ranging from 0.1-3 mm) |
| **Sub-function(s) or/and Extra-function(s)** | As per description in section 5.3.1 |
| **Object of sub/extra-function(s)** | As per description in section 5.3.1 |
| **Context of Sub/Extra-action(s)** | *Process Condition*: Description of context of the sub or extra function(s)<br>Ex: for dermal denticles reducing flag on shark's skin the context could be: "water" |
| **Biological Strategy** | As per description in section 5.3.1 |
| **Biological Mechanism** | As per description in section 5.3.1 |

| Field in the database | Description |
|---|---|
| **Short description of mechanism** | From the biological mechanism, a short description of the working principle is provided including some of its features which could be of interest to the sector (ex: cross-flow filtration with flow reversal) |
| **Separation Principle** | This field includes a short definition of the separation principles. This allows selecting records of the database according to separation principles and explores different mechanisms nature utilizes to carry them out.<br>Ex: membrane diffusion, depth filtration, surface dead end, etc. |
| **Active/ Passive** | *Process Attribute: Active*: energy provided by the organism to carry out function; *Passive*: exploit free energy available in external environment |
| **Scale** | *Process Attribute:* The scale of the elements separated from the main fluid. Ex: atomic/molecular, micro(nm-µm), meso (mm), macro (mm-cm) |
| **Flow details** | *Process Condition***:** Parameters of the flow: ex: Reynolds number, velocity, temperature, etc. |
| **Energy/Driving Force** | *Process Condition***:** In case of both Active or Passive system, describe main energy fuelling the process of separation: ex: gravity, gradient of pressure, etc. |
| **Environmental conditions** | As per description in section 5.3.1 |
| **Process Diagram/Pics** | As per description in section 5.3.1 |
| **Extracted Design Principle** | As per description in section 5.3.1 |
| **References** | As per description in section 5.3.1 |

*Table 6-3: Fields of the GB-BID database for the function "to separate"*

### 6.3.1 Populating the Database

Functions are initially extracted from strategies and mechanisms utilized in Separation Technology Sector than refined via the Biomimicry Taxonomy, the NIST Functional Basis and Engineering-to-Biology thesaurus. Furthermore synonymous have been identified and reviewed through WORDNET. Below a final list of functions identified:

- *To Separate, To Divide, To Filter, To Extract, To Excrete, To Expel, To Trap, To Capture, To Attract, To Repel, To Exclude, To Remove, To Attach, To Detach, To Sediment, To Precipitate, To Absorb, To Adsorb, To Convert, To Transform, To Exchange.*

To be noticed that to structure the functions according to a hierarchy is not considered appropriate and useful as some of the functions can be considered strategies of other functions and the other way around. For instance: "filtering" is a strategy of separation (separate by filtering) and "capturing" could be a strategy to filter (filtering by capturing) but also the other way around (capturing by filtering).

The functions have been utilized to start the biological search that proceeded according to the following steps as explained in section 3.3.3:

1. *Consult AskNature*: AskNature was consulted in several rounds in 2016, 2018 and 2020. Changes in relevant entries have been noticed during this period. As AskNature is updated with a crowdsourcing approach, the researcher believes that the new entries regarding organisms whose strategy relates to separation derived from the Global Biomimicry Design Challenges launched by the Biomimicry Institute (biomimicry.org - responsible for the management of AskNature) between 2015 and 2019. The Challenges had a strong relation with separation technologies (the challenges were about how to improve the Food Systems, to combat Climate Change and deal with Ocean plastic and microplastics). This stimulated the competitors to explore the function "to separate" more in depth and new organisms were added dealing with that function over 2016-2019.

2. *Explore the scientific references provided by AskNature.* Scientific references proposed were consulted when accessible.
3. *Explore additional references* derived from the previous ones or searched via specific keywords. All papers consulted were peer-reviewed and published in relevant Journals or Conferences proceedings.
4. *Extracting and storing the information* in the database. Texts have been sometimes re-written, sometimes directly copied in the relevant fields of the database. References have been mentioned which can also provide pictures and drawing of the biological processes in order to better understand them.

In most of the cases, several papers were consulted for each organism and biological solution in order:

- To clarify as much as possible the biological strategy and mechanisms involved so as to be able to describe it in a concise and understandable way also by non-biologists;
- To identify photos, diagrams, drawings explaining the biological mechanisms;
- To identify values for the object, process and context's properties. For instance, size of filtered particles, Reynolds numbers, velocities, etc.

The Guild-based BID Database on Separation has been create in MS Excel environment and it is currently updated with 118 records. The full database is proposed in Annex 7. Below some preliminary statistics:

- Number of records: 118 of which 40 are also available in AskNature;
- Animals: 85; Plants: 25; Bacteria: 2, Eukariote cell: 5; Fungi: 1;
- Active/Passive strategy: 65% of the organisms deploy active strategies and 35% passive ones;
- Energy: 45% of the organisms utilizes dynamic pressure gradients; 25% uses surface energy (associated with gravity or pressure gradients); 15% uses metabolic energy; 15% uses chemical potential/osmosis/gradient of concentration.

In several cases information were not available or not detailed to fill up certain fields of the table (ex: particle size, flow regime, diagram of process) however assessing information about the context within which the function is carried out, at least some qualitative estimate on certain parameters (Ex: Reynolds number) could be done. Below an example of a record from the database (Figure 6-7).

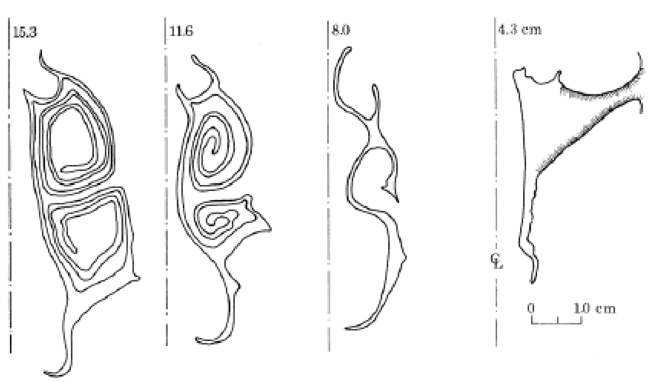
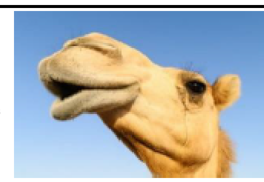
| | | | | | |
|---|---|---|---|---|---|
| **Biological Organism** | Camel | **Phenotype** | Respiratory system - Nasal turbinates | **Environmental conditions** | Desert environment with high T excursion night/day |
| **Main Action** | Extract | **Object of main action** | Moisture | **Context of main action** (Process condition) | Air |
| **Sub/Extra-action 1** | Condense/Evaporate | **Object action 1** | Moisture | **Context of Action 1** (Process condition) | air |
| **Sub/Extra-action 2** | Exchange | **Object action 2** | Heat | **Context of Action 2** (Process condition) | air |
| **Biological strategy description** | **Nasal turbinates** which **extract and recover air moisture** from breathing as well as **exchange heat.** In camels the recovery of water caused by nasal heat exchange might reach 70 % of the potential respiratory water loss. The main site at which the heat and water exchange occurs has been identified as the turbinate structures of the nasal passages. | | | | |
| **Biological Mechanism** | **Nasal turbinates have a 3 D convoluted spiraling structure** which optimizes surface/volume ration as well as creates favourable turbulences and **allow to evaporate and condensate humidity.** The increased surfaces of the nasal passageways, which posses **hygroscopic property**, are cooled by the inhaled air and because of evaporation (loss of latent heat) they may be cooled to below the temperature of the inhaled air. On exhalation the air that passes over the cool surfaces gives up heat, water recondenses, and the exhaled air may even be below ambient temperature. | | | | |
| **Mechan. in short** | Phase change - condensation/evaporation | **Active/ Passive** (Process attribute) | AC/PA | **Scale** (Process attribute) | Atomic/Molecular/Micro |
| **Objective's properties** | water molecoles | **Flow details** (Process condition) | Re high (turbulent) | **Energy** (Process condition) | Dynamic pressure gradient Surface energy |
| **Extracted Design Principle** | Spiraling/convoluted folded layer (with transversal section oriented perpedicularly to the direction of the fluid) which maximize surface on which fluid passes without increasing pressure losses due to increased length of obstacles to the flow. | | | | |
| **Process diagrams and pics** |    Transversal sections of the turbinates at different distances from the larinx | | | | |

*Figure 6-7: One of the entries extracted from the GB-BID database and organized according to a specific template used during the ideation workshops (see Chapter 7) (not all the fields of the database are included in the template).*

## 6.3.2 The importance of the Sub-functions and Extra-functions

In the records, several sub-functions characterizing the separation mechanism have been highlighted as well as some extra-functions not directly related to the separation process but that are carried out by the system performing the separation anyway. These additional sub and extra functions not only enrich the

description of the separation process facilitating the extraction of useful design principles but they can also act as *connecting functions* with future other similar GB-BID databases related to different sectors/functions.
For instance in many of the biological mechanisms identified, the sub-function "move liquids" or "manage liquids" or "reduce drag" or extra-functions such as "exchange heat" or "reduce adhesion" have been identified and classified. This could allow:

1. Using already the GB-BID database on separation to generate bio-inspired ideas on problems not related with separation but with other functions such as "move liquids", "exchange heat" and "regulate adhesion";
2. Connecting the GB-BID databases among different functions. Relevant biological knowledge as well as extracted design principles can be retrieved when preparing other GB-BID databases so as to expand the solutions space for the ideation process for each database using information from the others.

### 6.3.3 Challenges in populating the database

Several challenges determined the current version of the database:

- Information about biological mechanisms are sometimes not clear or still at the level of speculation;
- Biological literature is not easily available open-source and for some organisms, papers are dated back to 50-70 years ago;
- Diagrams or drawings of processes are not frequent. More often biological literature extensively describes forms and processes with texts and in biology technical language without using drawing or schematic diagrams; available photos are often not enough to clarify processes;
- Identification of operating conditions such as Reynolds number, velocity, etc. was definitively the most difficult part as biological literature does not often report hydraulic conditions. In most of the cases for instance the Reynold number has been just largely estimated considering the supposed type of flow laminar or turbulent;
- Extracting and/or drafting the description of the biological mechanism has been a time consuming exercise. Process which is still on-going refining the information encoded. Following the time spent in researching in scientific literature, extracting the mechanism is the process affecting the most cost of the setting up of the GB-BID database;
- Identifying the separation principle is sometimes not straightforward as several actions are concurring in the process. It is considered more effective to keep a relatively extensive description of the process and let the user of the table to decide which element to be considered in the process of principle extraction;
- Extracting the design principles is affected by subjectivity as it has been carried out by the researcher.

Overall, it should be highlighted that the current table is a first attempt of storing biological information in an effective way for carrying out a BID process. The researcher utilized the table for extracting initial insights (see Chapter 8) but the process of organizing information and reviewing text to make the entries clearer is still on-going. The process would definitively benefit from a multidisciplinary process, involving biologists and experts in separation technology.

## 6.4 The Evolutionary Innovation Model of the Separation Technology sector

In order to leverage the potentiality for ideation of the GB-BID database on Separation an appropriate framework embedding some of the principles of the Evolutionary Innovation Model has to be set up.
Following the description of the Separation Technology Sector of section 6.2.3, Figure 6-3 and the principles identified in sections 5.1.1 a framework for a coopetitive open innovation model of the Separation Technology sector is proposed.
Table 6-4 indicates main stages in the production of separation technologies and supply chain involved highlighting elements for creating coopetitive partnerships for using the GB-BID database for ideas generation.

| | Stages in Separation tech. industry | Cooperation in the supply chain | Competition at stages level |
|---|---|---|---|
| **1** | • Basic material for separation media/elements made<br>• Other-than-separation media/elements materials made | The sector have examples of firms carrying out all stages as well as supply chain system with firms dealing with stage 1, stages 2/3/4 and stage 5 separately or stage 1, stages 2/3 and stages 4/5.<br><br>Cooperation can be seek at all levels. | Manufacturers from stage 1 to 4 may compete in separation tech sector but also in other sectors for different end-user's products (construction sector, automotive) |
| **2** | • Separation media/element's material processed<br>• Other-than-separation media/elements materials processed | | |
| **3** | • Bulk formation of separation media/elements<br>• Other-than-separation media/elements parts processed | | |
| **4** | • Conversion of the bulk medium material to fit into the filter device | | |
| **5** | • Separation device assembly and sales. | | May compete in diverse sub-segments of the market of separation technology |

*Table 6-4: Separation technology industry (from (Sutherland 2008)) and possible Cooperation/Competition set ups (elaborated by the researcher).*

A possible framework is pictured in Figure 6-8 where firms, belonging to different stages of production – TIER - (different "guilds" from a biological perspective), both cooperating or competing in the separation technology sector or in different sectors, may enter into partnership to develop and utilize the GB-BID database. Cooperating along the supply chain, where members belonging to each stage bring know-how about problems and solutions for each stage, would increase the effectiveness of the ideation process. The participation of customers is also expected in the logic of a demand-pull innovation process.

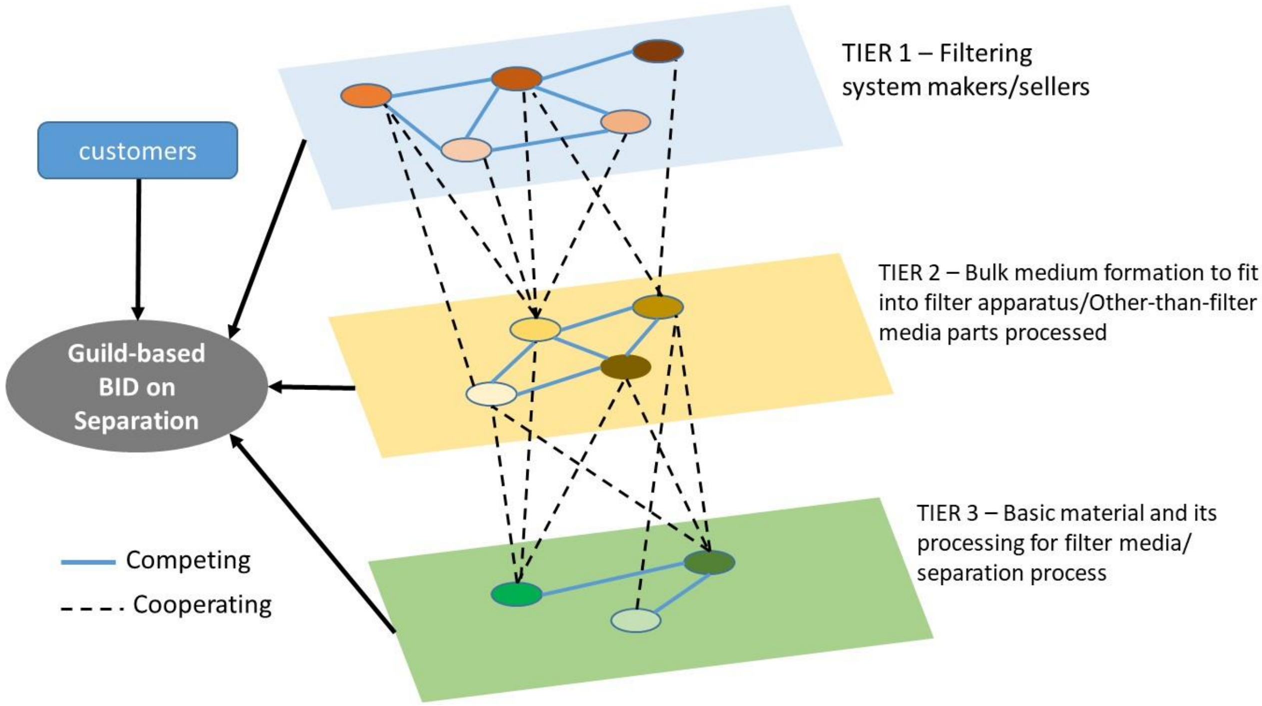



*Figure 6-8: Proposal for framework for partnership for developing and using Guild-Based BID method for Separation Technologies. Possible competitors at each Tier level but co-operators across levels.*

The chapter framed the Sector object of the testing in validation process as well as provided the description of the specific tools derived from the EIM and the GB-BID method applied to the sector of Separation Technology. The EIM remains a conceptual output and the GB-BID Database is tested via Ideation workshops (Chapter 7) and Case studies (Chapter 8).

# 7. TESTING AND VALIDATION – Ideation Workshops

## 7.1 Workshop's Material preparation

In order to provide biological stimuli to the participants, nine biological solutions were selected from the GB-BID database. Eight of them to be utilized in the problem-driven approach and an additional one for the solution-driven approach.
The biological information was prepared in the four different formats:

1. A table containing information from some of the fields of the GB-BID database (GBBID);
2. A table containing information from some of the fields of the GB-BID database prepared by a non-expert (a newly graduated student of management engineering) (NE-GBBID);
3. A sheet containing information taken from some of the fields of the GB-BID but organized according to the ontology of the SBF-DANE method;
4. A sheet with information cut-and-pasted directly from AskNature.

Because the workshops were held sometimes in English and sometimes in Italian, the information originally in English have been translated when needed.
In Figure 7-1 below, three different templates utilized with biological information (GB-BID and NE-GBBID have the same template). An example of completed tables is provided in Annex 8.

| AskNature Template |
|---|
| **One line text describing the Biological Strategy as extracted from AskNature** |
| Pictures of the Organisms/Phenotype and pictures or drawings of the Biological mechanism as extracted from AskNature |
| Expanded textual description of the biological strategy and mechanisms as extracted from AskNature |

| GB-BID and NE-GBBID Template | | | | | |
|---|---|---|---|---|---|
| **Biological Organism** | | **Phenotype** | | **Environmental conditions** | |
| **Main Action** | | **Object of main action** | | **Context of main action** (Process condition) | |
| **Sub/Extra-action 1** | | **Object action 1** | | **Context of Action 1** (Process condition) | |
| **Sub/Extra-action 2** | | **Object action 2** | | **Context of Action 2** (Process condition) | |
| **Biological strategy description** | | | | | |
| **Biological Mechanism** | | | | | |
| **Mechan. in short** | | **Active/ Passive** (Process attribute) | | **Scale** (Process attribute) | |
| **Objective's properties** | | **Flow details** (Process condition) | | **Energy** (Process condition) | |
| **Extracted Design Principle** | | | | | |
| **Process diagrams and pics** | | | | | |

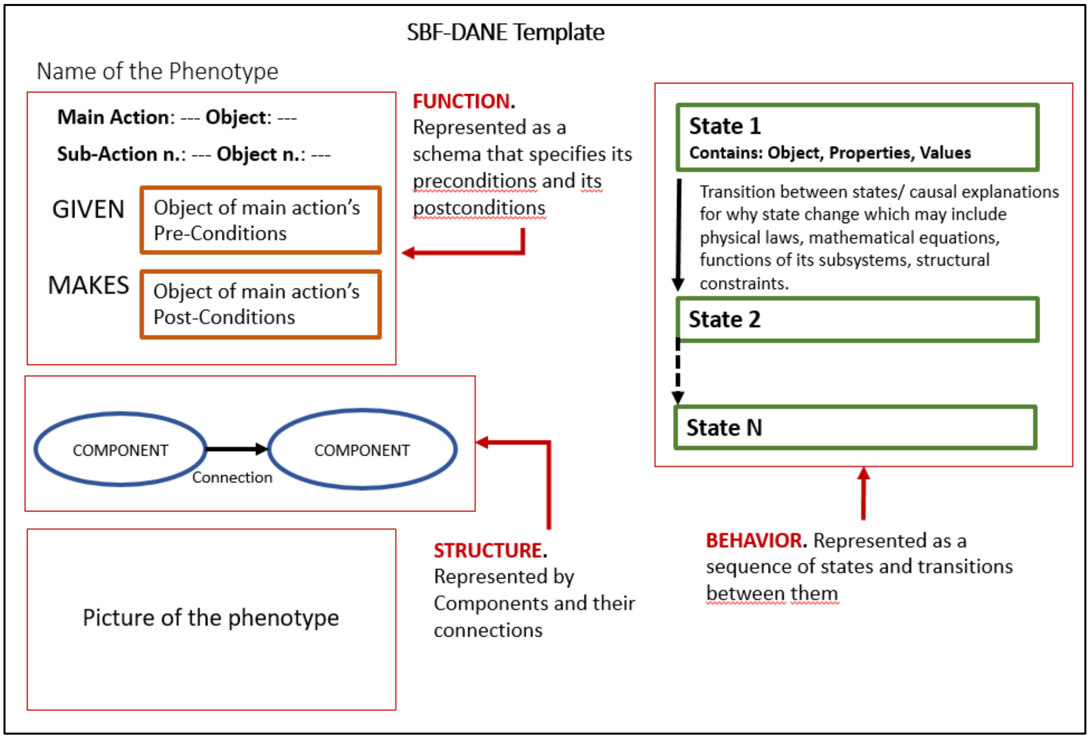



*Figure 7-1: Example of the three different formats for biological information provided during the ideation workshops: AskNature (upper); GB-BID and Non Expert GB-BID (middle); SBF-DANE (lower).*

Furthermore, considering the limited duration of the ideation workshops compared to the amount of information provided to be assessed, a summary list of the eight biological solutions was prepared (see extract in Figure 7-2 below) and provided to the participants working with the GBBID, NE-GBBID and SBF-DANE methods. This information is already present in the sheets of the GB-BID method and foreseen in the DANE ontology. The list was however not provided to the participants working with AskNature as this type of synthetic information is not available in AskNature but in the title itself of each biological solution.

List of Organisms

| N. | Organism name - Super System | System | Biological strategy description |
|---|---|---|---|
| 1 | Lotus plant (Nelumbo Nucifera) | Leaf surface | In order to stay clean in wet and muddy environment and photosyntetize, the leaf of the Lotus self cleans thanks to its superhydrophobic and low adhesion property which allow to **repel water and particles** |
| 2 | Cell | Intra/Extracellular Transport | Cell expels/introduces necessary molecules/particles via **intracellular energy-consuming transport** such as **Exocitosys** and **endocytosis.**<br>**Exocytosis.** Process by which a cell directs the contents of **excretory vesicles** out of the cell membrane and into the extracellular space.<br>**Endocytosis** is the counterpart of exocytosis and it is again a form of transport in which a vescicle transports molecules into the cell from the extracellular space. |
| 3 | Camel | Respiratory system - Nasal turbinates | **Nasal turbinates** which **extract** and recover **air moisture** from breathing as well as **exchange heat**.<br>In camels the recovery of water caused by nasal heat exchange might reach 70 % of the potential respiratory water loss. The main site at which the heat and water exchange occurs has been identified as the turbinate structures of the nasal passages. |
| 4 | Stenocera beetles (Onymacris unguicularis) | Body surface (integument) | The Stenocara beetle in the Namib Desert uses the combination of hydrophilic/superhydrophobic patterned surface of its wings to collect drinking water from fog-laden wind. In a foggy dawn, the Stenocara beetle tilts its body forward into the wind to capture small water droplets in the fog. After these small water droplets coalesce into bigger droplets, they roll down into the beetle's mouth, providing the beetle with a fresh morning drink. |
| 5 | Caddis fly | Net | Larvae build flexible net that traps nutrients in water. The mesh itself stop sediments. Grid expands depending on sediments load to avoid clogging. |

*Figure 7-2: Summary list of biological solutions provided during the ideation workshop.*

The participants were provided with a format for reporting ideas which allow providing their code as members of a team, the code of the biological solutions they took inspiration from, a textual description of the idea and a sketch (Figure 7-3).

| |
|---|
| **Code:** |
| **Organisms number:** |
| **Description** |
| **Sketch:** |

*Figure 7-3: sheet to report ideas.*

## 7.2 Workshop challenges/Limitations

In organizing the workshops the following challenges have been identified which required compromises in order to, at least partially, respond to all of them and which most probably affected the results of the workshops:

1. *Difficulty in recruiting participants*. When the workshop is conducted in academic environment, it is easier to allocate time for it and to involve students. When workshop needs to be carried out outside Academia there are obvious difficulties in identifying and recruiting interested participants. On the other hand, because this research is carried out precisely to find more effective ways to bring BID

outside the academic environment, and in the light of testing the Evolutionary Innovation Model together with the GB-BID method, more efforts were made to seek for participants in the industrial sector. The fact of learning a new approach to generate innovative ideas as well as doing it using biological knowledge was utilized to stimulate curiosity of potential participants and attract them to the workshops. Both usefulness and originality in the approach were important elements of attractiveness for both mixed-background participants and knowledge-based experts. Nevertheless, the participation to workshops outside academia has not been as such to gather data to make conclusive statistical analysis.

2. *Not enough time allocated for workshops*. The duration of the workshops was determined based on previous published experiences and considering the availability of potential participants both in Academia but especially from the industrial sector. Because of the amount of biological information to be consulted and utilized (nine biological solutions), possibly not enough time was allocated to absorb the information so as to be able to utilized them at full creative potential.
3. *Keep the motivation and creativity potential during the workshops*. Because of an overall duration of the workshops spanning between 2,5 to 4 hours (In some cases the solution-driven approach was not carried out and only one problem-driven approach was conducted instead of two of them), the participants may suffer for mental exhaustion in generating ideas. Splitting the workshop in phases could have had pros and cons, allowing participants incubation time and time to interact among themselves outside the experiment set up and therefore biasing the results.

A series of workshops were conducted following the procedures highlighted in Chapter 3 section3.3.5:

| Place and date | Context | N. of particip. | Type of participants | Comments |
|---|---|---|---|---|
| Milan 14/09/19 | Public event on sustainability (Milano Green Forum) | 7 | Mixed background, age (22-55 yrs) | Because of the reduced number of participants the workshop was utilized as initial “dry test”. No teams were formed but each participant worked on his/her own. Language: *Italian* |
| Cyprus/ Nicosia 24/09/19 | Private event at premises of the company Isotech Ltd | 12 | Mixed technical background and age (25-68 yrs). Mainly chemical/environmental engineering | Isotech is a Cypriot consulting/applied research company in environmental issues. Staff members plus some external people participated<br>Language: *English* |
| Milan 30/10/19 | Politecnico di Milano | 41 | Student of Mechanical Engineering + 5 members from ENEL (age 23-30 yrs) | This workshop was held within the course of Inventive Problem Solving carried out by Prof. Gaetano Cascini.<br><br>Language: *English* |
| Brescia 14/11/19 | Digital Universitas | 20 | Mixed background, mainly technical age (25-55 yrs) | Digital Universitas is an organization specialized in vocational training/ professional requalification in Digital Technology, IoT and Mechatronic<br>Language: *Italian* |
| Milan 13/02/20 | Politecnico di Milano | 12 | Separation Technology experts | members from R&D departments of Italian companies specialized in Separation Technology<br>Language: *Italian* |

*Table 7-1: List of workshop held during the research.*

## 7.3 Workshop with Mixed participants

### 7.3.1 Ideation Workshop at Milano Green forum

The first workshop was promoted via the yearly event called Milano Green Forum. The Forum is a platform for exchanging ideas and dialogue around sustainability topics. It is open to the public and therefore the topics are presented in order to be easily. Unfortunately (despite an initial interest manifested with the on-line registration of 45 people), the participation was minimal. Only 7 people attended and all but one without specific knowledge about Separation Technologies. Therefore, being the number of participants too low to generate teams and produce some meaningful statistics, the workshop was carried out as a "dry run", to see how people from different background, gender and ages (22-55 years) would have reacted working singularly throughout the full programme as specified in section 3.3.5.
Ideation metrics were not calculated but Quantity of ideas (a single rater assessed). The questionnaire has been filled up at the end of the workshop.

**No-stimuli session**: – Problem: *how would you remove pollutant particles from air in city environment?* The following quantity of ideas were generated:

| Participant background | Quantity |
|---|---|
| 1 – Degree Eng. Design | 3 |
| 2 – Degree in Law | 3 |
| 3 – Student in Manag. Eng | 4 |
| 4 – Student in Philosophy | 0 |
| 5 – No university decree | 1 |
| 6 – Chemist - PhD | 2 |
| 7 – Economist | 2 |

*Table 7-2: Quantity of ideas generated by participants (highlighted their background) during the no-stimuli session at the Milano Green Forum workshop.*

All the ideas generated were of technical nature involving type of technological processes or devices. Following this session, a presentation on BID and its methods to be applied in the following sessions was provided.

**With Biological Stimuli - Problem Driven: 1st Challenge** – Problem: *how would you remove/collect humidity from air in city environment? (Possibly using low energy or passive method)* – 15' where allowed to study the material (8 organisms in the 4 different formats). Each participant received one specific format providing biological information.
The following quantity of ideas were generated:

| Participant background | Format of biological solution | Quantity | n. of biological solution utilized |
|---|---|---|---|
| 1 – Degree Eng. Design | DANE | 3 | 3+ |
| 2 – Degree in Law | NE-GBBID | 2 | 2 |
| 3 – Student in Manag. Eng | GBBID | 2 | 3+ |
| 4 – Student in Philosophy | GBBID | 1 | 1 |
| 5 – No university decree | AskNature | 1 | 1 |
| 6 – Chemist - PhD | DANE | 1 | 3+ |
| 7 – Economist | AskNature | 2 | 4+ |

**+** = more biological solutions in one technical solution

*Table 7-3: Quantity of ideas generated by participants (highlighted their background and the format of biological solution utilized) and the number of biological solutions utilized during the with-stimuli session – 1st challenge - at the Milano Green Forum workshop.*

All the ideas were of technical nature involving type of technological processes or devices.

**With Biological Stimuli - 2nd Challenge**: - Problem: *how would you remove oil and microplastic from a creek/river? (Possibly using low energy or passive method).* Each participant utilized the same format of biological solutions of the previous session. The following quantity of ideas were generated:

| Participant background | Format of biological solution | Quantity | n. of biological solution utilized |
|---|---|---|---|
| 1 – Degree Eng. Design | DANE | 3 | 3 |
| 2 – Degree in Law | NE-GBBID | 2 | 2 |
| 3 – Student in Manag. Eng. | GBBID | 1 | 2+ |
| 4 – Student in Philosophy | GBBID | 1 | 1 |
| 5 – No university decree | AskNature | 0 | |
| 6 – Chemist - PhD | DANE | 1 | 3+ |
| 7 – Economist | AskNature | 1 | 2+ |

*Table 7-4: Quantity of ideas generated by participants and the number of biological solutions utilized during the with-stimuli session – 2nd challenge - at the Milano Green Forum workshop.*

All the ideas were of technical nature involving type of technological processes or devices.

**With Biological Stimuli - Solution Driven session: –** Instruction: *generate as much as possible solutions to different problems inspired by the two biological solutions provided*

Only two biological solutions were provided to the participants. One biological solution was already present in their initial set of eight solutions, so participants were familiar with it, and one new biological solution (the toucan beak) was provided. Formats have been however swapped so participants could try two formats different from the previous sessions (Table 7-5). The following quantity of ideas were generated:

| Participant background | Previous format utilized | Format of biological solution known | Format of new biological solution | Quantity | n. of biological solution utilized |
|---|---|---|---|---|---|
| 1 – Degree Eng. Design | DANE | GBBID | GBBID | 2 | 1 |
| 2 – Degree in Law | NE-GBBID | AskNature | GBBID | 1 | 1 |
| 3 – Student in Manag. Eng | GBBID | DANE | AskNature | 2 | 2 |
| 4 – Student in Philosophy | GBBID | AskNature | DANE | 1 | 1 |
| 5 – No university decree | AskNature | GBBID | GBBID | 0 | 0 |
| 6 – Chemist - PhD | DANE | GBBID | AskNature | 0 | 0 |
| 7 – Economist | AskNature | NE-GBBID | DANE | 1 | 1 |

*Table 7-5: Quantity of ideas generated by participants and the number of biological solutions utilized during the Solution Driven session at the Milano Green Forum workshop. Indicated also the formats for biological solution utilized by each participant.*

All the ideas were of technical nature involving type of technological processes or devices.

*Final considerations following Questionnaire answers and discussions:*

- All the biological solutions provided have been utilized to generate ideas.

- Individual creativity as well as technical background play a role. More ideas were produced by the participants with technical background (Engineering). However other participants without technical background could produce some technical solutions. In particular participant n.7, despite the background in economy, showed quite a level of creativity.
- Among the formats of biological solutions, DANE was scored as the least satisfactory, however it did not prevent users to generate ideas. AskNature was scored low by engineers (because of not enough details) and high by non-technical people. GB-BID and NE-GBBID got high score in general by all participants who used it.
- Among the format of information provided, Text, Infographics of the processes and Photos have been scored progressively as the most useful.

### 7.3.2 Ideation Workshop at Isotech - Cyprus

This workshop was organized within the premises of the company Isotech/AKTI (http://www.isotech.com.cy/) that operates in the sector of environment in Cyprus with activities of consultancies, environmental education as well as applied research in environmental topics (water and waste reuse and disposal, coastal zone management, environmental decision-support systems). Knowledge of Separation Technology was present at different level of depth.
The 12 participants, the majority with engineering background, were divided in 4 groups of 3 members each and with at least one engineer in each group to test all the four methodologies (Table 7-6).
Because of time constraints requested by the company (2,5 hours), only one problem-driven challenge was proposed and the solution-driven approach was not carried out.
Also in the case, being the number of participants too low to generate more than one team for treatment group and produce some meaningful statistics, ideation metrics were not calculated but Quantity of ideas (only single rater). The questionnaire has been filled up at the end of the workshop.
Despite the lack of sufficient teams within treatment groups to calculate significant statistics, also this workshop helped in understanding teams dynamics, pros and cons of this type of workshop (especially because people with engineering background were involved) and obtaining useful information through questionnaire.

| **Participants** | **Background and years of experience** |
|---|---|
| Group 1 | 2 Chemical Eng. (25 yrs exp.), N.A. |
| Group 2 | Chemical Eng. (8 yrs), Env. Education (15 yrs), Environmental Eng. (3 yrs) |
| Group 3 | Biochemist /Env. Eng (9 yrs), Chemical Eng. (7yrs), Env. Eng. (2yrs) |
| Group 4 | Economist/Adm. Research proj. (24), Chemical Eng. (40yrs), Physicist (1 yrs) |

*Table 7-6: Background of participants in each treatment group of the workshop at Isotech.*

**No-stimuli session**: Problem: *how would you remove pollutants particles from air in city environment?*
The following quantity of ideas were generated:

| **Participants** | **Quantity** | **Type of idea** |
|---|---|---|
| Group 1 | 19 | Planning/Policy advices, Technology |
| Group 2 | 13 | Planning/Policy advices, Technology |
| Group 3 | 10 | Planning/Policy advices, Technology |
| Group 4 | 8 | Technology |

*Table 7-7: Quantity and type of ideas generated by groups of treatment during the no-stimuli session of the workshop at Isotech.*

It is considered relevant to highlight that the type of ideas generated where mixed; planning/policy advices as well as technological.

Following this session, a presentation on BID and its methods to be applied in the following sessions was provided.

**With Biological Stimuli - Problem Driven:** Problem: *how would you remove/collect humidity from air in city environment? (Possibly using low energy or passive method)* – 15' where provided to study the material (8 biological solutions in the 4 different formats). The following quantity of ideas were generated:

| Group of treatment | Format of biological solution | Quantity | Type of idea | n. of biological solution utilized | Comments |
|---|---|---|---|---|---|
| Group 1 | GBBID | 6 | Technology | 3 | 1 member left before completing |
| Group 2 | AskNature | 4 | Technology | 3 | 1 member left before completing |
| Group 3 | NE-GBBID | 8 | Technology | 4 | 2 are expanded ideas |
| Group 4 | DANE | 7 | Technology | 5 | 2 are expanded ideas |

*Table 7-8: Quantity and type of ideas generated by groups of treatment during the with-stimuli session of the workshop at Isotech.*

To be highlighted, differently from the non-stimuli session, the technological nature of all the ideas generated.

*Final considerations following Questionnaire answers and discussions:*

- The Questionnaire (see Annex 4) was duly completed by only 5 participants;
- The solution proposed in the brainstorming sessions where rather general and related to planning/policy advices. Only Group 4 provided more technical solutions. This may be due to the consultancy nature of the business of many participants. The situation changed during the session with biological stimuli, because reinforced by the researcher, where participants provided all technical solutions.
- Duration of exercise vis-a-vis information provided may have affected production of ideas in both modalities (problem/solution driven). The workshop seems too short to absorb and utilize all the material provided;
- The extracted principles proposed (in GBBID and NEGBBID) has been considered constraining creativity in 3 participants on 5;
- Despite Novelty and Quality metrics have not been formally assessed, considering both the originality of the ideas and the background of the participants who generated them, the rater noticed that none of the technical solutions are existing on the market and all of them may somehow be feasible following specific R&D;
- Among the formats of biological solutions, DANE scored as the least satisfactory in respect to several criteria, however it did not prevent users to generate ideas. AskNature scored low by engineers (not enough details) and high by non-technical people. GBBID and NE-GBBID got high score in general by all participants who used it.

| Indicators of applicability utilized for evaluating formats of biological solutions | DANE | ASKN. | GBBID | NEGBBID |
|---|---|---|---|---|
| Biological modelling capacity | 2.3 | 2.0 | 4.5 | 4.0 |
| Swiftness | 2.0 | 3.0 | 3.5 | 3.5 |

| | | | | |
|---|---|---|---|---|
| Simplicity | 2.3 | 2.0 | 3.5 | 5.0 |
| Field adaptability | 3.0 | 3.0 | 4.0 | 4.0 |
| Multi-domain capacity | 2.7 | 3.0 | 3.5 | 3.0 |

*Table 7-9: Scoring of criteria for assessing different formats of biological solutions (1 Very Weak – 5 Very Strong) – Workshop at Isotech.*

- The List of Organisms was provided for all the methodologies. It was considered useful to have a quick overview on organisms and quickly understand their strategies;
- Among the format of information provided, Text, Infographics of the processes and Photos have been scored progressively as the most useful scoring respectively 2.0, 2.0 and 2.4 (1-most useful, 4-less useful).

### 7.3.3 Ideation Workshop at Digital Universitas

This workshop was held at the premises of Digital Universitas (https://www.digitaluniversitas.com/), a specialized training private school who has two main courses: one in digital technologies and IoT and one in Mechatronics. It was introduced in a module of three hours of lesson where the first hour was dedicated to a general introduction to biomimicry. Students were mixed in terms of background and ages in their search for re-training themselves for other occupations. 20 participants attended with age between 19 and 49 years and with highly diverse background such as: Economy, Chemistry, Languages, Engineering, ICT, Graphics, Psychology and no High Education degree. Their knowledge about BID has been declared by them as follow:

| % on Total | Level of BID knowledge |
|---|---|
| 77.78% | Not at all familiar |
| 16.67% | Slightly familiar |
| 5.56% | Moderately familiar |
| 0.00% | Extremely familiar |

*Table 7-10: Knowledge of BID of participants at Digital Universitas workshop. Only 18 on 20 compiled the final questionnaire*

The participants were divided into 10 teams of two members each and groups of treatments were formed as follows: GB-BID three teams, AskNature three teams, DANE three teams and NE-GBBID only one team. Because of the number of teams it was indeed decided to give less relevance to the NE-GBBID in favour of the other methods.
Because of the team of two members and the time limit for the overall workshop (2 hours), the brain-sketch rotation procedure was reduced to 15’-10’.

#### *Scoring ideas generated and calculating metrics*

In order to calculate the ideation metrics, the ideas generated during the sessions of this workshops have been assessed by 2 raters experts in the sectors of Biomimicry as well as Separation Technologies: one is the researcher and one is a junior engineer designer with 4 years of experience in bio-inspired innovation in the separation technology sector (and Master thesis on bio-inspired oil-water separation).
The procedure to evaluate the sets of ideas, described in detail in

Table 3-11, has been discussed beforehand in order to create common understanding on how to score the various metrics. Furthermore, around 10% of the ideas generated in both rounds (the ones with and without stimuli) has been evaluated by both raters together in order to consolidate common understanding. Then the evaluation proceeded separately. Data have been recorded in MS Excel environment and the researcher made the necessary averages of the scores and calculated the metrics.

### *Implementation of the workshop*

**No-stimuli session**: Problem: *how would you remove plastic from the oceans?*
At the end of the session the ideas were collected (see examples in Figure 7-4) and rated by the two raters. Through a Mann-Whitney U test it was confirmed their agreement (Table 7-11)

| Factor/metric | Quantity | Novelty | Quality | Variety |
|---|---|---|---|---|
| U | 50.0 | 50.0 | 32.5 | 44.5 |
| U critical .01 | 16 | 16 | 16 | 16 |
| U critical .05 | 23 | 23 | 23 | 23 |
| **if U > Ucrit** the null hypothesis cannot be rejected, so two evaluators are in agreement | | | | |

*Table 7-11: Results of M-W test for non-stimuli session of workshop at Digital Universitas*

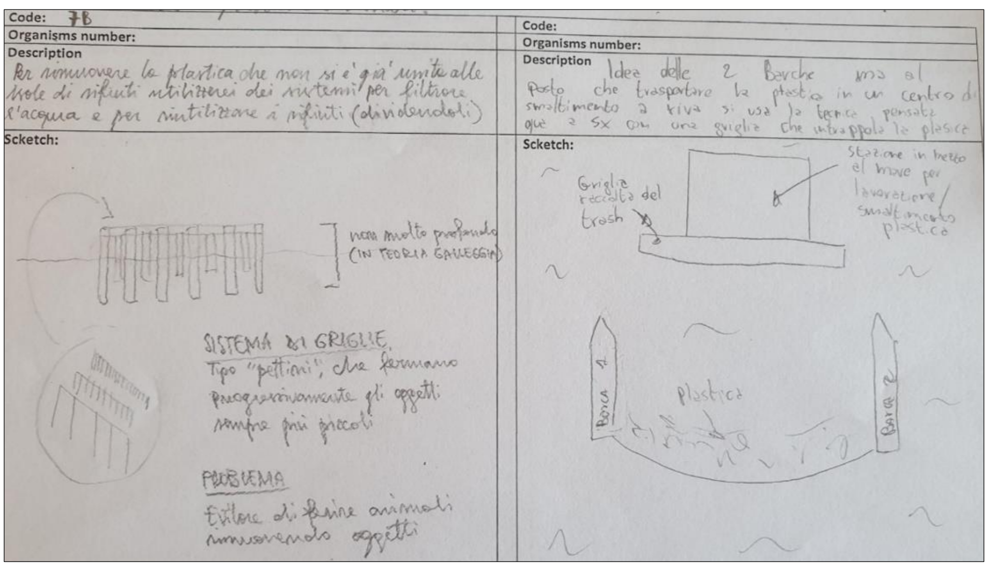



*Figure 7-4: Samples of ideas generated during the no-stimuli session at Digital Universitas.*

The scores provided by the raters were averaged:

| | GBBID1 | GBBID2 | GBBID3 | AskN1 | AskN2 | AskN3 | Dane1 | Dane2 | Dane3 | NEGBIBID |
|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | 4.00 | 4.00 | 5.00 | 3.00 | 2.00 | 4.00 | 3.00 | 2.50 | 3.50 | 3.00 |
| Av. Novelty | 6.88 | 6.88 | 6.53 | 6.67 | 2.50 | 7.33 | 5.56 | 3.75 | 5.35 | 3.33 |
| Av. Quality | 1.25 | 0.88 | 0.71 | 1.00 | 0.50 | 0.90 | 1.00 | 1.00 | 0.88 | 1.00 |
| Variety | 25.00 | 27.50 | 40.00 | 20.00 | 12.50 | 30.00 | 17.50 | 15.00 | 27.50 | 20.00 |
| Max Nov | 2.13 | 2.13 | 2.38 | 1.67 | 0.00 | 2.20 | 1.67 | 1.13 | 1.67 | 1.00 |
| Max Qual | 4.50 | 3.00 | 4.00 | 2.50 | 0.00 | 3.00 | 3.00 | 1.50 | 3.00 | 3.00 |
| Percentage Q | 87.50% | 87.50% | 87.50% | 100.00% | 25.00% | 90.00% | 100.00% | 100.00% | 87.50% | 100.00% |
| Percentage N | 87.50% | 75.00% | 100.00% | 33.33% | 0.00% | 50.00% | 0.00% | 50.00% | 25.00% | 0.00% |

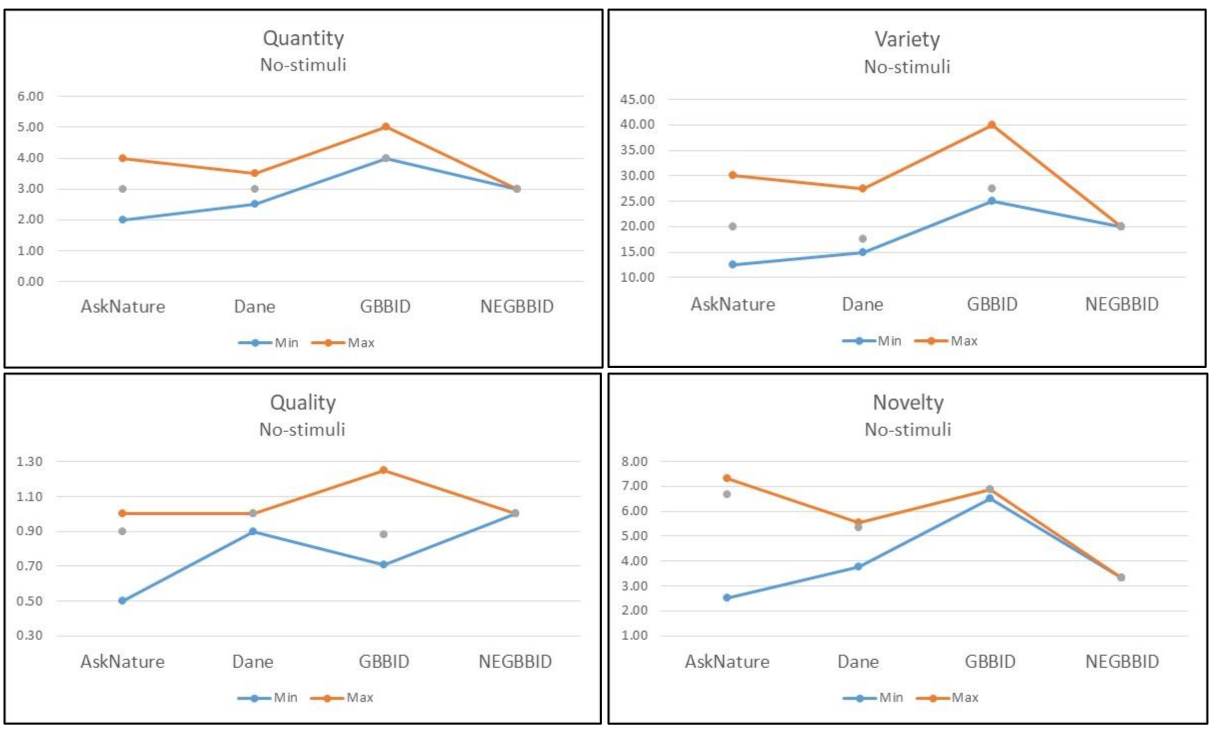
*Table 7-12: Workshop at Digital Universitas – No-Stimuli session. Metrics of teams of groups of treatment. The code for each team refers to the BID method utilized by the team during the session with biological stimuli.*

A Kruskal-Wallis test was carried out to assess if there was a statistically significant difference among the metrics calculated for the different groups of treatment. This aimed at verifying that they did not differ in their performance and that the random distribution of participants generated teams with similar ideas generation capacity.

| Factor/metric | Quantity | Novelty | Quality | Variety |
|---|---|---|---|---|
| **H** | 8.782 | 5.582 | 13.082 | 7.445 |
| ***X2*** | 6.600 | 6.600 | 6.600 | 6.600 |
| | X2<H | X2>H | X2<H | X2<H |
| Rejected null hypothesis? | YES | NO | YES | YES |

*Table 7-13: Results of Kruskal-Wallis test for non-stimuli session of workshop at Digital Universitas. X2 at 5% and (4-1) degrees using K-W table for 4 groups, three of which of three data each and one of one data (3,3,3,1)*

The results of the test (Table 7-13) show that in fact the teams *do not* behave uniformly (but on Novelty). This behaviour should be taken into consideration when drawing final results on the workshop following the session with biological-stimuli. Below in Figure 7-5 charts of the metrics as per data in Table 7-12:



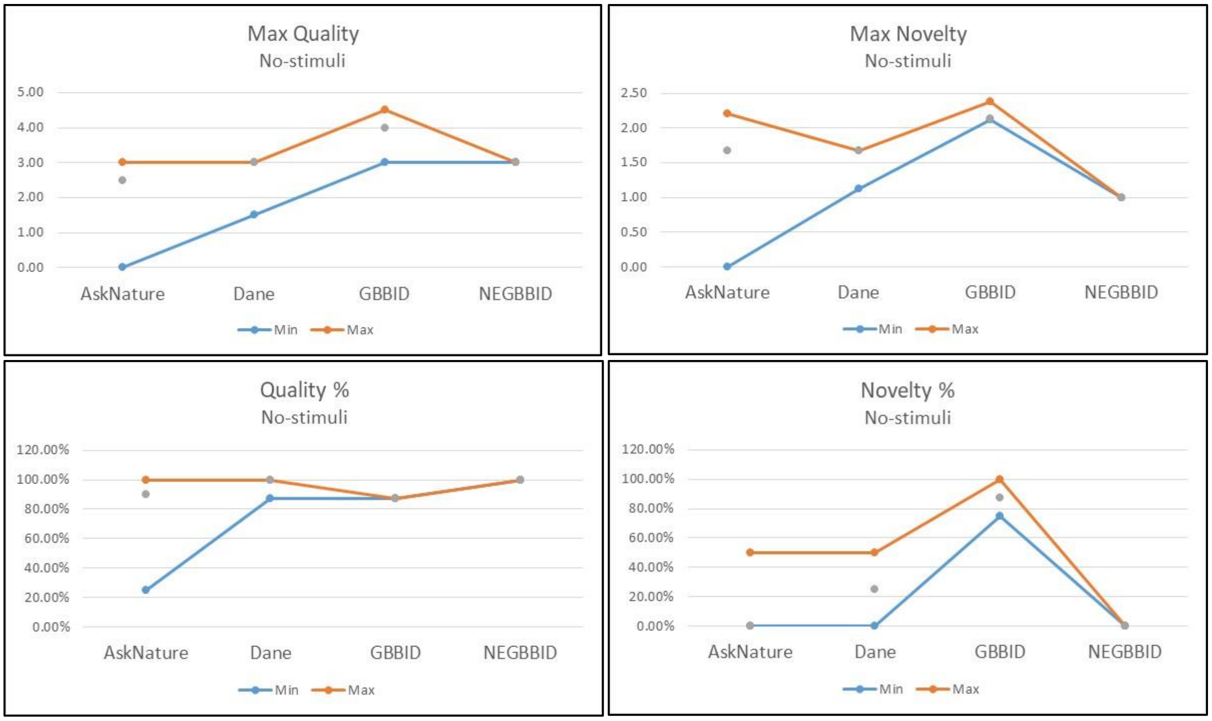



*Figure 7-5: Workshop at Digital Universitas - Metrics for the No-stimuli session for groups of treatment – The points in the graphs represent the values of a specific metric within the group of treatment (formed by mainly by three teams, so three distinct points per treatment group unless some values coincide - NEGBBID is represented by one team only). Among the values, Min and Max have been highlighted.*

Following this session, a presentation on BID and its methods to be applied in the following sessions was provided.

**With (Biological) Stimuli session – Problem-Driven:** Problem: *how would you remove/collect humidity from air in city environment? (Possibly using low energy or passive method)* – 15' where provided to study the material (8 biological solutions in the 4 different formats)
At the end of the session the ideas were collected (see examples in Figure 7-6) and rated by two raters. Through a Mann-Whitney U test it was confirmed their agreement (Table 7-14).

| Factor/metric | Quality | Novelty | Quality | Variety | Originality | BioEmul. |
|---|---|---|---|---|---|---|
| U | 41.5 | 40.5 | 44.0 | 38.0 | 42.0 | 32.5 |
| U critical .01 | 16 | 16 | 16 | 16 | 16 | 16 |
| U critical .05 | 23 | 23 | 23 | 23 | 23 | 23 |
| **if U > Ucrit** the null hypothesis cannot be rejected, so two evaluators are in agreement | | | | | | |

*Table 7-14: Results of M-W test for session with-stimuli of workshop at Digital Universitas*

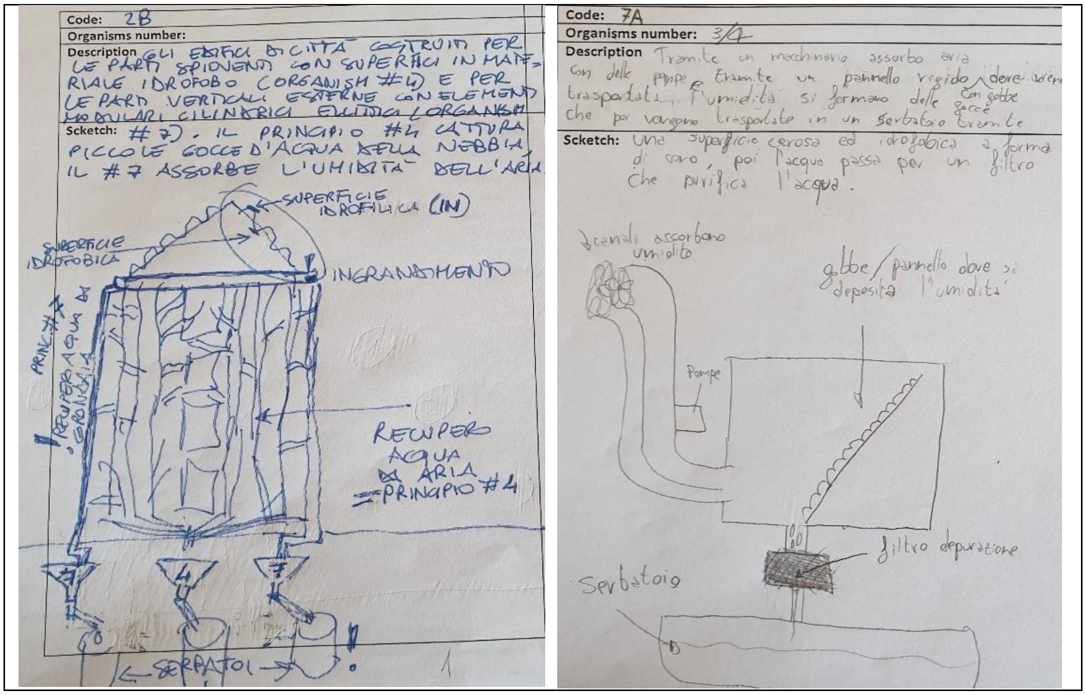



*Figure 7-6: Samples of ideas generated during the biological-stimuli session at Digital Universitas.*

The scores provided by the raters were averaged:

| | GBBID1 | GBBID2 | GBBID3 | AskN1 | AskN2 | AskN3 | Dane1 | Dane2 | Dane3 | NEGBIBID |
|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | 2.50 | 3.00 | 1.50 | 1.50 | 0.00 | 2.00 | 3.00 | 1.00 | 1.50 | 1.50 |
| Novelty | 4.72 | 6.67 | 2.50 | 5.00 | 0.00 | 3.33 | 0.00 | 0.00 | 2.50 | 2.50 |
| Quality | 1.00 | 0.67 | 1.00 | 0.25 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.75 |
| Variety | 12.50 | 20.00 | 5.00 | 10.00 | 0.00 | 10.00 | 20.00 | 0.00 | 5.00 | 5.00 |
| Originality | 3.17 | 5.67 | 3.00 | 2.25 | 0.00 | 2.50 | 4.33 | 7.00 | 3.00 | 5.00 |
| Bio-Emulation | 1.00 | 7.00 | 3.00 | 3.00 | 0.00 | 3.17 | 4.00 | 10.00 | 1.00 | 5.50 |
| Novelty H-cr. | 7.60 | 9.33 | 6.25 | 6.50 | 0.00 | 8.33 | 5.00 | 8.00 | 7.25 | 5.80 |
| Novelty P-cr. | 1.00 | 1.78 | 2.50 | 0.00 | 0.00 | 0.89 | 0.00 | 0.00 | 1.50 | 1.00 |
| Max Nov | 0.67 | 2.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.50 |
| Max Qual | 1.50 | 2.00 | 0.00 | 0.00 | 0.00 | 1.50 | 3.00 | 1.00 | 2.00 | 0.50 |
| Percentage Q | 100.00% | 66.67% | 100.00% | 25.00% | 0.00% | 83.33% | 100.00% | 100.00% | 100.00% | 75.00% |
| Percentage N | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |

*Table 7-15: Workshop at Digital Universitas – with-stimuli session. Metrics of teams within groups of treatment.*

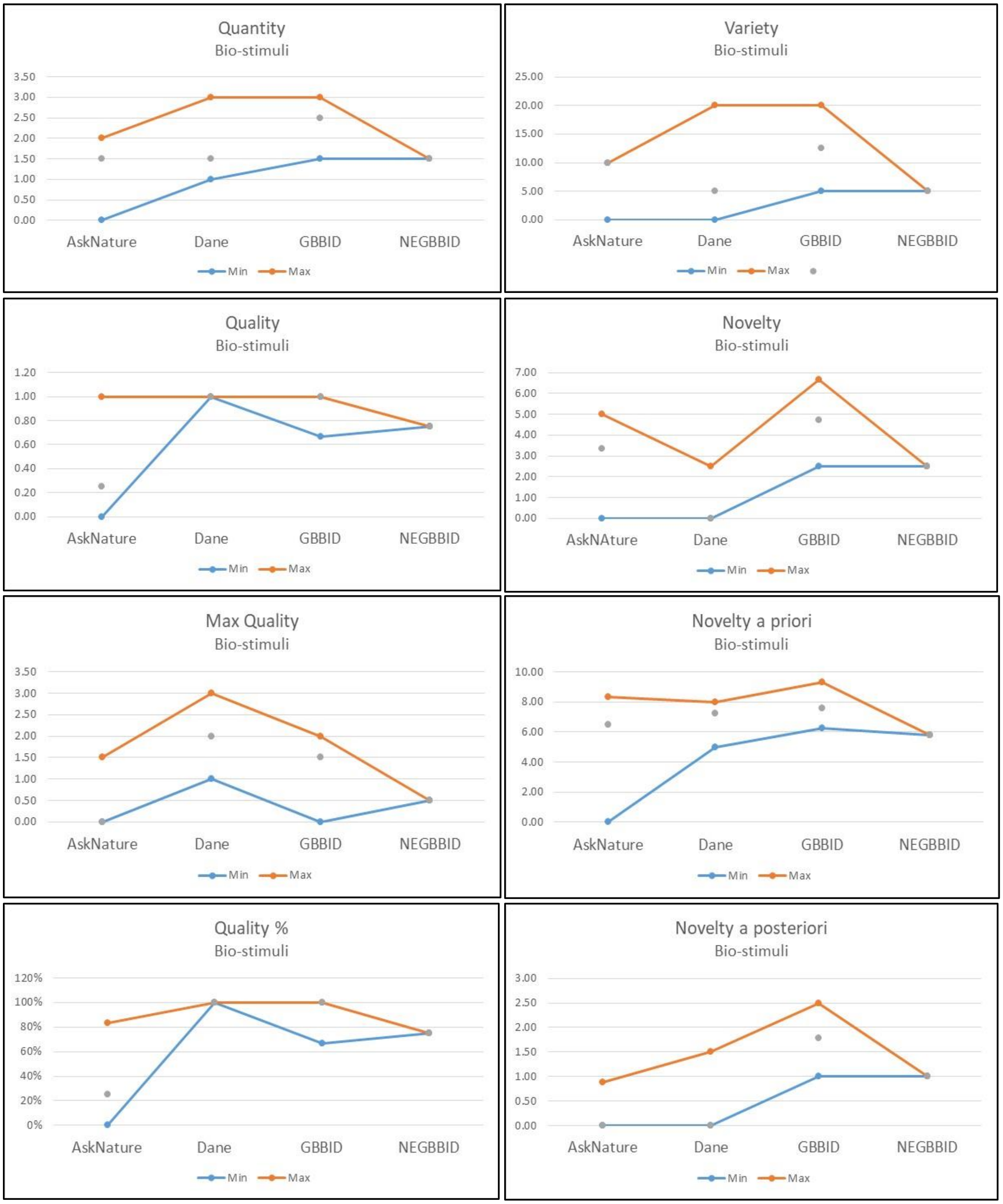
A Kruskal-Wallis test was carried out to assess if there was a statistically significant difference among the metrics calculated for the different groups of treatment (different BID methods):

| **Factor/metric** | **Quality** | **Novelty** | **Quality** | **Variety** | **Originality** | **BioEmul.** | **A priori Nov.** | **A post Nov.** |
|---|---|---|---|---|---|---|---|---|
| **H** | 1.800 | 3.691 | 2.945 | 1.382 | 5.927 | 1.927 | 1.509 | 5.036 |
| ***X2*** | 6.600 | 6.600 | 6.600 | 6.600 | 6.600 | 6.600 | 6.600 | 6.600 |
| | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H |
| Rejected null hypothesis? | NO | NO | NO | NO | NO | NO | NO | NO |

*Table 7-16: Results of Kruskal-Wallis test for with-stimuli session of workshop at Digital Universitas. X2 at 5% and (4-1) degrees using K-W table for 4 groups, three of which of 3 data each and one of one data (3,3,3,1)*

The test reveals no significant difference in the metrics among the different BID methods. So none of them can be considered more effective than the others.

Below in Figure 7-7 charts of the metrics as per Table 7-15:



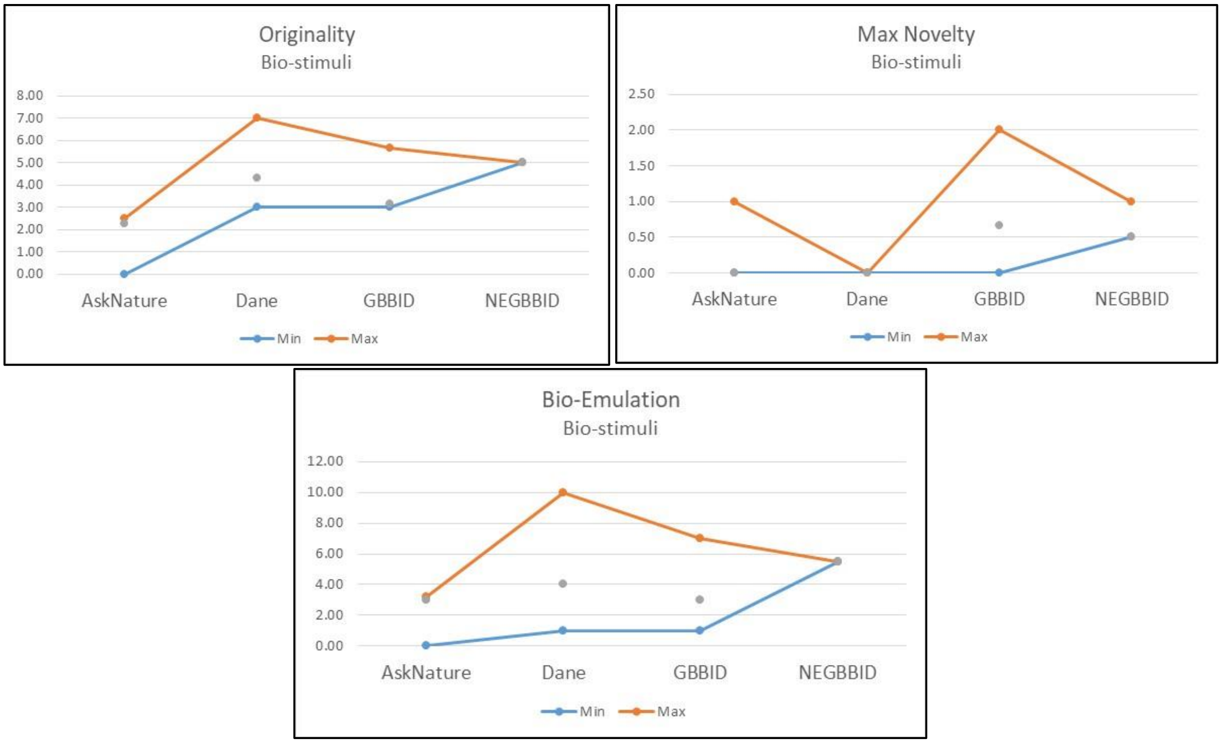



*Figure 7-7: Workshop at Digital Universitas. Metrics for the session with biological stimuli for groups of treatment. The points in the graphs represent the values of a specific metric within the group of treatment (formed by mainly three teams, so three distinct points per treatment group unless some values coincide - NEGBBID is represented by one team only). Among the values, Min and Max have been highlighted. To be noticed that one team on three working with Asknature scored 0 in all metrics. Furthermore the metric "Novelty %" is 0% for all groups and therefore it has not been reported in graph. GB-BID seems performing better than other BID methods on Novelty metrics.*

The above charts, despite a disproven significant difference in performance among BID methods, show a better performance of the GBBID in Novelty related metrics.

### *Comparing No-Stimuli/Biological-stimuli sessions*

Even if the problem to be solved was different between the session with and without stimuli, because it was of similar complexity as well as broad breath (high potential for many different solutions), an analysis of the variance was carried out between the two sessions utilizing the Mann-Whitney U test which provided the following results:

| **Factor/metric** | **Quality** | **Novelty** | **Quality** | **Variety** | **Max Nov.** | **Max Qual.** | **Perc. Qual.** | **Perc. Nov.** |
|---|---|---|---|---|---|---|---|---|
| **U** | 9.0 | 15.5 | 45.0 | 8.5.0 | 12.5 | 16.0 | 43.5 | 15.0 |
| **U critical .01** | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| **U critical .05** | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 |
| | U < Ucrit | U < Ucrit | U > Ucrit | U < Ucrit | U < Ucrit | U < Ucrit | U > Ucrit | U < Ucrit |
| Rejected null hypothesis? | YES | YES | NO | YES | YES | YES | NO | YES |

*Table 7-17: Results of M-W test on comparison between the sessions with and without stimuli of workshop at Digital Universitas*

The test reveals a statistically significant difference in the metrics between the two sessions. This is also highlighted in the Table 7-18 below comparing the averages of metrics. From these data it appears that no-stimuli session was more effective than the one with stimuli.

| Metric | Session | GBBID | AskNature | DANE | NEGBBID |
|---|---|---|---|---|---|
| **Quantity** | Bio-Stimuli | 2.33 | 1.17 | 1.83 | 1.50 |
| | No-Stimuli | 4.33 | 3.00 | 3.00 | 3.00 |
| | difference% | **-46.2%** | **-61.1%** | **-38.9%** | **-50.0%** |
| **Av. Novelty** | Bio-Stimuli | 4.63 | 2.78 | 0.83 | 2.50 |
| | No-Stimuli | 6.76 | 5.50 | 4.88 | 3.33 |
| | difference% | **-31.5%** | **-49.5%** | **-82.9%** | **-25.0%** |
| **Av .Quality** | Bio-Stimuli | 0.89 | 0.42 | 1.00 | 0.75 |
| | No-Stimuli | 0.94 | 0.80 | 0.96 | 1.00 |
| | difference% | **-5.9%** | **-47.9%** | **4.3%** | **-25.0%** |
| **Variety** | Bio-Stimuli | 12.50 | 6.67 | 8.33 | 5.00 |
| | No-Stimuli | 30.83 | 20.83 | 20.00 | 20.00 |
| | difference% | **-59.5%** | **-68.0%** | **-58.3%** | **-75.0%** |
| **Max Nov** | Bio-Stimuli | 0.89 | 0.33 | 0.00 | 0.50 |
| | No-Stimuli | 2.21 | 1.29 | 1.49 | 1.00 |
| | difference% | **-59.7%** | **-74.1%** | **-100.0%** | **-50.0%** |
| **Max Qual** | Bio-Stimuli | 1.17 | 0.50 | 2.00 | 0.50 |
| | No-Stimuli | 3.83 | 1.83 | 2.50 | 3.00 |
| | difference% | **-69.6%** | **-72.7%** | **-20.0%** | **-83.3%** |
| **Percentage Q** | Bio-Stimuli | 88.89% | 36.11% | 100.00% | 75.00% |
| | No-Stimuli | 87.50% | 71.67% | 95.83% | 100.00% |
| | difference% | **1.4%** | **-35.6%** | **4.2%** | **-25.0%** |
| **Percentage N** | Bio-Stimuli | 0.00% | 0.00% | 0.00% | 0.00% |
| | No-Stimuli | 87.50% | 27.78% | 25.00% | 0.00% |
| | difference% | **-87.5%** | **-27.8%** | **-25.0%** | **0.0%** |

*Table 7-18: Workshop at Digital Universitas - Comparison of averages of metrics between sessions with and without stimuli.*

Another aspect to be highlighted is that in the no-stimuli session the ideation capacity of teams within the group of treatment appeared not uniform (null hypothesis rejected via Mann-Whitney U test) where in the session with biological stimuli this non-uniformity seemed levelled out.

### *Relevant consideration from the Questionnaire*

The following considerations have been derived from some of the questions replied by participants:

Which is the format of biological information you find more useful for the purpose?

| Score | Frequency | Text | Freq. | Graphs | Freq. | Drawing | Freq. | Photo |
|---|---|---|---|---|---|---|---|---|
| **1** | 2 | 13.33% | 3 | 27.27% | 1 | 7.14% | 2 | 14.29% |
| **2** | 2 | 13.33% | 1 | 9.09% | 2 | 14.29% | 1 | 7.14% |
| **3** | 4 | 26.67% | 5 | 45.45% | 1 | 7.14% | 4 | 28.57% |
| **4** | 3 | 20.00% | 1 | 9.09% | 9 | 64.29% | 2 | 14.29% |
| **5** | 4 | 26.67% | 1 | 9.09% | 1 | 7.14% | 5 | 35.71% |
| | **Total score** | **50** | | **29** | | **49** | | **49** |
| | **Average score** | **3.33** | | **2.64** | | **3.50** | | **3.50** |

*Table 7-19: Scores on preference of formats of biological information. Percentages for each score for each format type (text, graph, drawing, photo), total scores and averages.*

Both drawings and photos scored the highest, textual information follows.

Did your background influence the creative process?

| Score | Freq. | % |
|---|---|---|
| **1** | 6 | 35.29% |
| **2** | 8 | 47.06% |
| **3** | 2 | 11.76% |
| **4** | 0 | 0.00% |
| **5** | 1 | 5.88% |

*Table 7-20: Percentages of scores on influence of participants background on their creative process*

Did you apply existing technologies to generate ideas?

| Score | Freq. | % |
|---|---|---|
| **1** | 6 | 35.29% |
| **2** | 4 | 23.53% |
| **3** | 4 | 23.53% |
| **4** | 2 | 11.76% |
| **5** | 1 | 5.88% |

*Table 7-21: Percentages of scores on use of concepts of existing technology by participants in their creative process*

Most likely due to the mixed background (often not technical) of participants, both background and application of existing technologies did not play a major role in the generation of ideas.
Because the workshop did not foresee exchange of formats of biological solutions among the teams, the related questions on their applicability have not been considered.

### *Final Considerations*

From the results of this workshop, taking into consideration the profile of the participants and their potential level of motivation in the exercise, the following aspects seem emerging:

- The ideation capacity of the teams appeared not uniform in the session without stimuli but it levelled out in the session with stimuli, during which, however, the ideation metrics resulted lower (one team using AskNature could not produce any idea).
- The Kruskal-Wallis test reveals no significant difference in the metrics among the different BID methods.
- Based on the above, it appears that the biological stimuli instead of improving ideas generation had the effect of reducing it. This could be due to the setup of the workshop where time constraint vis-à-vis amount of biological information to review may have created a blockage in the capacity of generating bio-inspired ideas due to overwhelming availability of information.
- To be also said that the difference in the problems to be solved between the sessions with and without stimuli, despite their similar complexity and broad breath, may have also played a role in this difference between the sessions.
- The broad breath of the problems, selected in order to guarantee a consequent broad breath of solutions, may have also played a role in the results. Having selected a more specific problem with more constraints and therefore with a narrower breath for solutions, could have possibly pushed participants in using biological analogies in a more effective way.
- The assessment of ideation metrics seems indicating that mixed-background participants can utilize the GB-BID method to generate ideas with a certain level of variety, quality and novelty. The participants did not perceive their background influencing the creative process.

## 7.4 Ideation Workshop with Engineering Students

This workshop was held at the Politecnico di Milano involving students of Mechanical Engineering within their course of Methods and Tools for Systematic Innovation. 41 participants of which 5 were external to the University but still with engineering background. Participants are almost all between 23 and 24 years old and their knowledge about BID has been declared by them as follow:

| % on Total | Level of BID knowledge |
|---|---|
| 10.8% | Not at all familiar |
| 56.8% | Slightly familiar |
| 16.2% | Moderately familiar |
| 16.2% | Extremely familiar |

*Table 7-22: Knowledge of BID of participants at workshop with engineering students. Only 37 on 41 compiled the final questionnaire*

The students had been already introduced to BID in general in one of their lessons, this may justify their answer.
Thanks to the number of participants, four treatment groups with at least three teams of three people each group were formed (one group had four teams).

### *Scoring ideas generated and calculating metrics*

In order to calculate the ideation metrics, the ideas generated during the sessions of this workshops have been assessed by 2 raters experts in the sectors of Biomimicry as well as Separation Technologies: one is the researcher and one is a junior engineer designer with 4 years of experience in bio-inspired innovation in the separation technology sector (and Master thesis on bio-inspired oil-water separation).
The procedure to evaluate the sets of ideas, described in detail in

Table 3-11, has been discussed beforehand in order to create common understanding on how to score the various metrics. Furthermore around 10% of the ideas generated in both rounds (the ones with and without stimuli) has been evaluated by both raters together in order to consolidate common understanding. Then the evaluation proceeded separately. Data have been recorded in MS Excel environment and the researcher made the necessary averages of the scores and calculated the metrics.

### *Implementation of the workshop*

**No-stimuli session**: Problem: *how would you remove pollutant particles from air in city environment?*
At the end of the session the ideas were collected (see example in Figure 7-8) and rated by two raters (the research and a graduated engineering design with three years of experience with experienced in BID). Both a Mann-Whitney U test (Table 7-23) and also a Kendall-W test (Table 7-24) confirmed their general agreement in rating with only some level agreement on novelty:

Mann-Whitney test:

| Factor/metric | Quantity | Novelty | Quality | Variety |
|---|---|---|---|---|
| **U** | 70.0 | 54.5 | 61.0 | 67.0 |
| **U critical .01** | 34 | 34 | 34 | 34 |
| **U critical .05** | 45 | 45 | 45 | 45 |
| **if U > U critical** the null hypothesis cannot be rejected: so two raters are in agreement | | | | |

*Table 7-23: Results of M-W test for non-stimuli session of workshop with engineering students.*

Kendall W test:

| Factor/metric | Quantity | Novelty | Quality | Variety |
|---|---|---|---|---|
| **k** | 13 | 13 | 13 | 13 |
| **m** | 2 | 2 | 2 | 2 |
| **W** | 0.859 | 0.631 | 0.789 | 0.763 |
| **TIES CORRECTIONS** | | | | |
| **W** | 0.904 | 0.645 | 0.808 | 0.779 |
| As W is > 0, the agreement between raters can be confirmed | | | | |

*Table 7-24: Results of Kendall W test for non-stimuli session of workshop with engineering students.*

The scores provided by the raters were averaged:

| | AskN1 | AskN2 | AskN3 | Dane1 | Dane2 | Dane3 | GBBID1 | GBBID2 | GBBID3 | GBBID4 | NEGBID1 | NEGBID2 | NEGBID3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | 10.00 | 5.00 | 3.50 | 4.00 | 5.50 | 2.00 | 5.00 | 6.50 | 4.00 | 5.00 | 6.50 | 4.50 | 4.50 |
| Av. Novelty | 8.10 | 7.92 | 7.08 | 6.88 | 6.50 | 5.00 | 7.20 | 6.32 | 6.88 | 7.03 | 7.70 | 7.35 | 6.33 |
| Av. Quality | 0.65 | 0.79 | 0.88 | 0.75 | 0.63 | 1.00 | 0.80 | 0.77 | 0.63 | 1.00 | 0.62 | 0.68 | 0.78 |
| Variety | 77.50 | 40.00 | 25.00 | 27.50 | 37.50 | 15.00 | 35.00 | 27.50 | 12.50 | 17.50 | 52.50 | 32.50 | 32.50 |
| Max Nov | 2.70 | 1.96 | 2.13 | 2.13 | 2.20 | 0.00 | 2.40 | 2.15 | 2.13 | 1.63 | 2.54 | 2.33 | 2.20 |
| Max Qual | 3.00 | 2.50 | 3.00 | 3.00 | 3.00 | 2.00 | 3.00 | 3.00 | 2.00 | 3.50 | 3.00 | 3.00 | 3.00 |
| Percentage Q | 65.00% | 87.50% | 87.50% | 75.00% | 63.33% | 100.00% | 90.00% | 77.38% | 87.50% | 90.00% | 70.24% | 55.00% | 77.50% |
| Percentage N | 90.00% | 100.00% | 50.00% | 75.00% | 66.67% | 0.00% | 60.00% | 36.90% | 75.00% | 70.00% | 78.57% | 80.00% | 75.00% |

*Table 7-25: Workshop with engineering students – No-Stimuli session. Metrics of teams of groups of treatment. The code for each team refers to the BID method utilized by the team during the session with biological stimuli.*

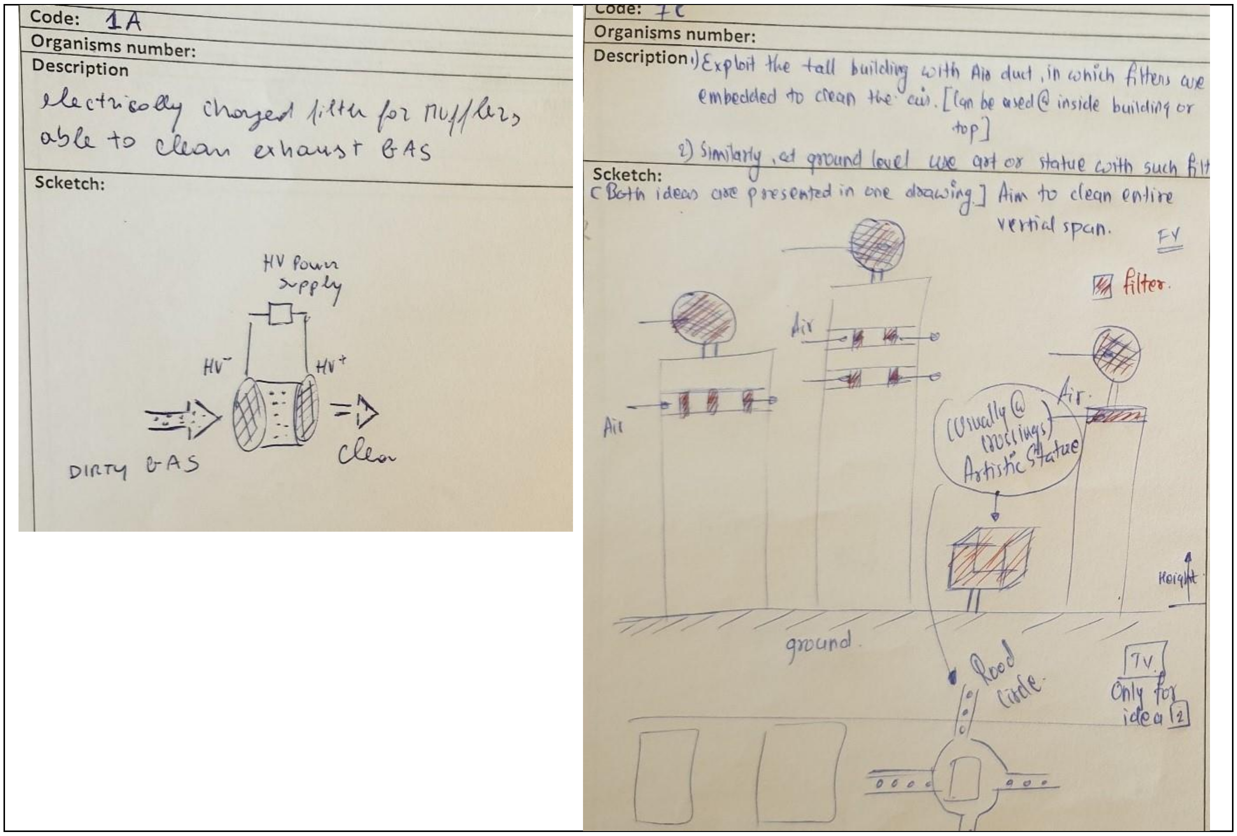



*Figure 7-8: Samples of ideas generated during the no-stimuli session with engineering students.*

A Kruskal-Wallis test was carried out to assess if there was a statistically significant difference among the metrics calculated for the different groups of treatment. This aimed at verifying that they did not differ in their performance and that the random distribution of participants generated teams with similar ideas generation capacity.

| Factor/metric | Quantity | Novelty | Quality | Variety |
|---|---|---|---|---|
| **H** | 1.214 | 6.120 | 1.482 | 3.625 |
| ***X2*** | 6.984 | 6.984 | 6.984 | 6.984 |
| | X2>H | X2>H | X2>H | X2>H |
| Rejected null hypothesis? | NO | NO | NO | NO |

*Table 7-26: Results of Kruskal-Wallis test for non-stimuli session of workshop with engineering students. X2 at 5% and (4-1) degrees using K-W table for 4 groups of 3 data each (4,3,3,3)*

The null hypothesis that the groups of treatment do not differ in their performance cannot be rejected. In Figure 7-9 below, charts of the metrics as per Table 7-25:

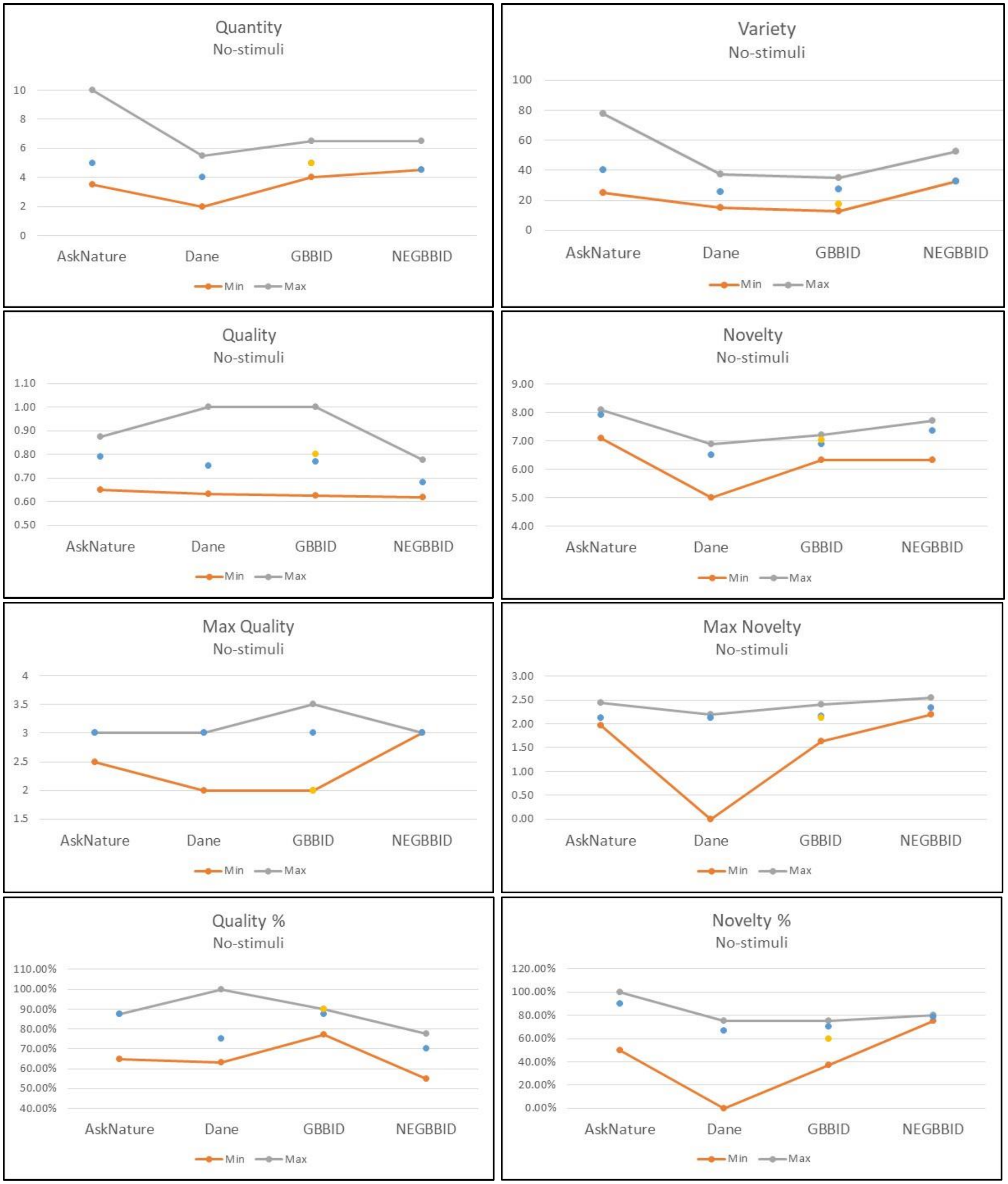



*Figure 7-9: Workshop with engineering students - Metrics for the No-stimuli session for groups of treatment – The points in the graphs represent the values of a specific metric within the group of treatment (formed mainly by three teams, so three distinct points per treatment group unless some values coincide - GBBID is represented by four teams). Among the values Min and Max have been highlighted.*

Following this session, a presentation on BID and its methods to be applied in the following sessions was provided.

**With (Biological) Stimuli – Problem-Driven:** Problem: *how would you remove/collect humidity from air in city environment? (Possibly using low energy or passive method)* – 15' where provided to study the material (8 biological solutions in the 4 different formats)
At the end of the session the ideas were collected (see example in Figure 7-10) and rated by the two raters. Both a Mann-Whitney U test (Table 7-27) and also a Kendall-W test (Table 7-28) confirmed their general agreement in rating with only some level agreement on novelty:

Mann-Whitney test:

| Factor/metric | Quantity | Novelty | Quality | Variety | Originality | BioEmul. | A priori Nov. | A post Nov. |
|---|---|---|---|---|---|---|---|---|
| **U*** | 76.5 | 82.5 | 46.5 | 84.5 | 72.5 | 52.5 | 70 | 81.5 |
| **U critical .01** | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 |
| **U critical .05** | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| **if U > U critical** the null hypothesis cannot be rejected | | | | | | | | |

*Table 7-27: Results of M-W test for with-stimuli session of workshop with engineering students.*

Kendall W test:

| Factor/metric | Quantity | Novelty | Quality | Variety | Originality | BioEmul. | A priori Nov. | A post Nov. |
|---|---|---|---|---|---|---|---|---|
| **k** | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| **m** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **W** | 0.859 | 0.631 | 0.789 | 0.763 | 0.769 | 0.738 | 0.701 | 0.673 |
| **TIES CORRECTIONS** | | | | | | | | |
| **W** | 0.904 | 0.645 | 0.808 | 0.779 | 0.808 | 0.753 | 0.723 | 0.694 |
| As W is > 0, the agreement between raters can be confirmed | | | | | | | | |

*Table 7-28: Results of Kendall W test for with-stimuli session of workshop with engineering students.*

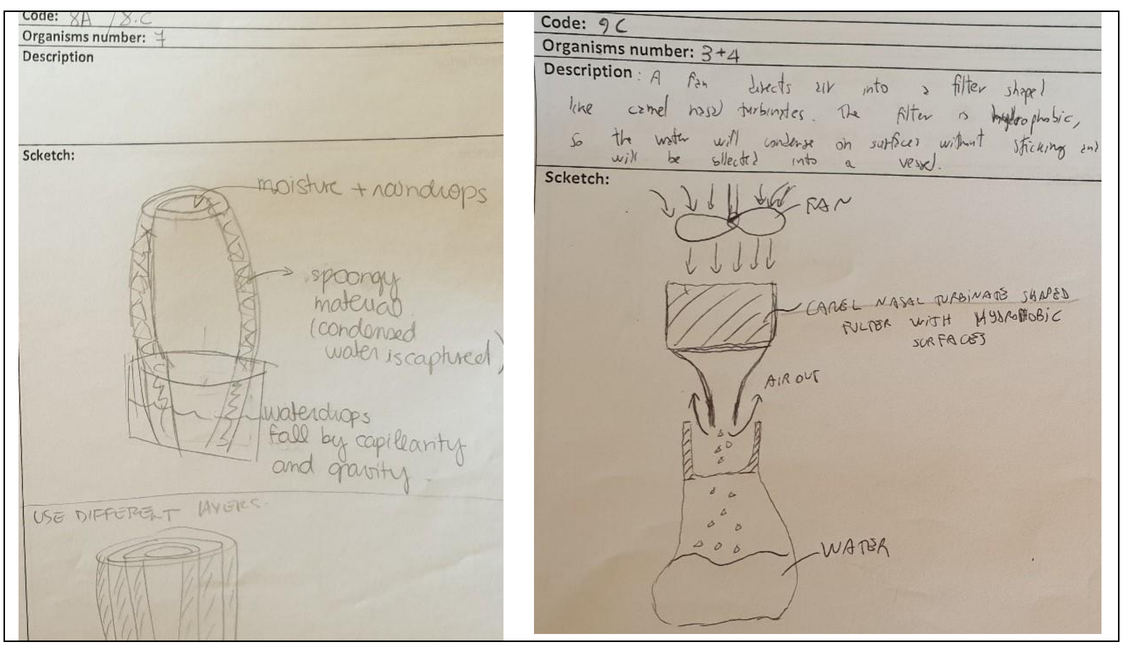


*Figure 7-10: Samples of ideas generated during the biological-stimuli session with engineering students.*

The scores provided by the raters were averaged:

| | AskN1 | AskN2 | AskN3 | Dane1 | Dane2 | Dane3 | GBBID1 | GBBID2 | GBBID3 | GBBID4 | NEGBID1 | NEGBID2 | NEGBID3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | 5.00 | 7.00 | 4.50 | 2.50 | 5.00 | 4.50 | 6.00 | 4.50 | 7.00 | 5.50 | 5.50 | 4.50 | 3.00 |
| Av. Novelty | 7.60 | 8.57 | 6.95 | 5.83 | 8.00 | 7.75 | 7.26 | 5.53 | 7.76 | 7.49 | 8.17 | 7.75 | 3.33 |
| Av. Quality | 0.90 | 0.71 | 0.45 | 0.58 | 0.70 | 0.90 | 0.75 | 0.68 | 0.86 | 0.82 | 0.98 | 0.98 | 1.00 |
| Variety | 37.50 | 60.00 | 35.00 | 15.00 | 40.00 | 35.00 | 40.00 | 22.50 | 50.00 | 45.00 | 50.00 | 35.00 | 15.00 |
| Originality | 3.60 | 3.64 | 2.43 | 4.33 | 2.50 | 2.70 | 3.17 | 2.33 | 3.36 | 4.10 | 3.10 | 3.10 | 3.00 |
| Bio-Emulation | 3.50 | 4.21 | 4.33 | 4.00 | 3.00 | 3.70 | 4.08 | 2.70 | 6.00 | 6.27 | 5.85 | 4.70 | 6.00 |
| A priori Nov. | 5.76 | 6.43 | 7.30 | 5.42 | 6.50 | 7.65 | 5.68 | 8.38 | 8.71 | 7.77 | 7.16 | 6.44 | 8.40 |
| A post. Nov. | 4.48 | 5.06 | 4.11 | 4.72 | 2.88 | 1.79 | 3.94 | 4.28 | 2.78 | 4.30 | 5.20 | 5.42 | 1.78 |
| Max Nov | 2.40 | 2.57 | 2.33 | 1.00 | 2.40 | 2.33 | 2.36 | 1.80 | 2.36 | 2.45 | 2.45 | 2.33 | 0.00 |
| Max Qual | 3.00 | 3.50 | 2.00 | 1.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.50 | 3.00 | 4.50 | 4.00 | 3.00 |
| Percentage Q | 90.00% | 71.43% | 45.00% | 83.33% | 70.00% | 70.00% | 75.00% | 67.50% | 85.71% | 81.67% | 80.00% | 77.50% | 100.00% |
| Percentage N | 80.00% | 100.00% | 100.00% | 0.00% | 100.00% | 100.00% | 33.33% | 25.00% | 92.86% | 83.33% | 100.00% | 100.00% | 0.00% |

*Table 7-29: Workshop with engineering student – with-stimuli session. Metrics of teams within groups of treatment.*

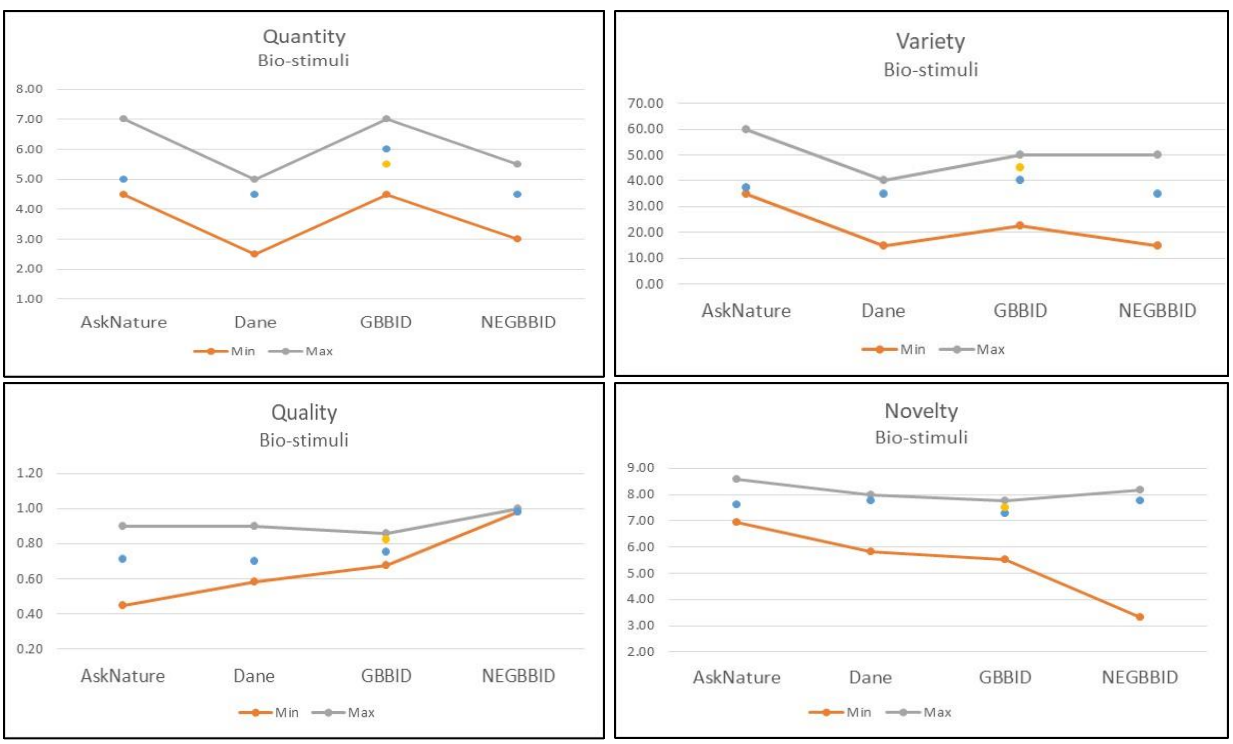
A Kruskal-Wallis test was carried out to assess if there was a statistically significant difference among the metrics calculated for the different groups of treatment.

| Factor/metric | Quantity | Novelty | Quality | Variety | Originality | BioEmu. | A priori Nov. | A post Nov. |
|---|---|---|---|---|---|---|---|---|
| **H** | 3.713 | 0.665 | 6.538 | 1.753 | 0.374 | 4.581 | 2.593 | 2.060 |
| ***X2*** | 6.984 | 6.984 | 6.984 | 6.984 | 6.984 | 6.984 | 6.984 | 6.984 |
| | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H | X2>H |
| Rejected null hypothesis? | NO | NO | NO | NO | NO | NO | NO | NO |

*Table 7-30: Results of Kruskal-Wallis test for with-stimuli session of workshop with engineering students.*
*X2 at 5% and (4-1) degrees using K-W table for 4 groups of 3 data each (4,3,3,3)*

The null hypothesis that the groups of treatment do not differ in their performance cannot be rejected. As a consequence, it can be stated that there is no difference in effectiveness among the different BID methods tested in any of the metrics calculated.

In Figure 7-11 below, charts of the metrics as per Table 7-29:



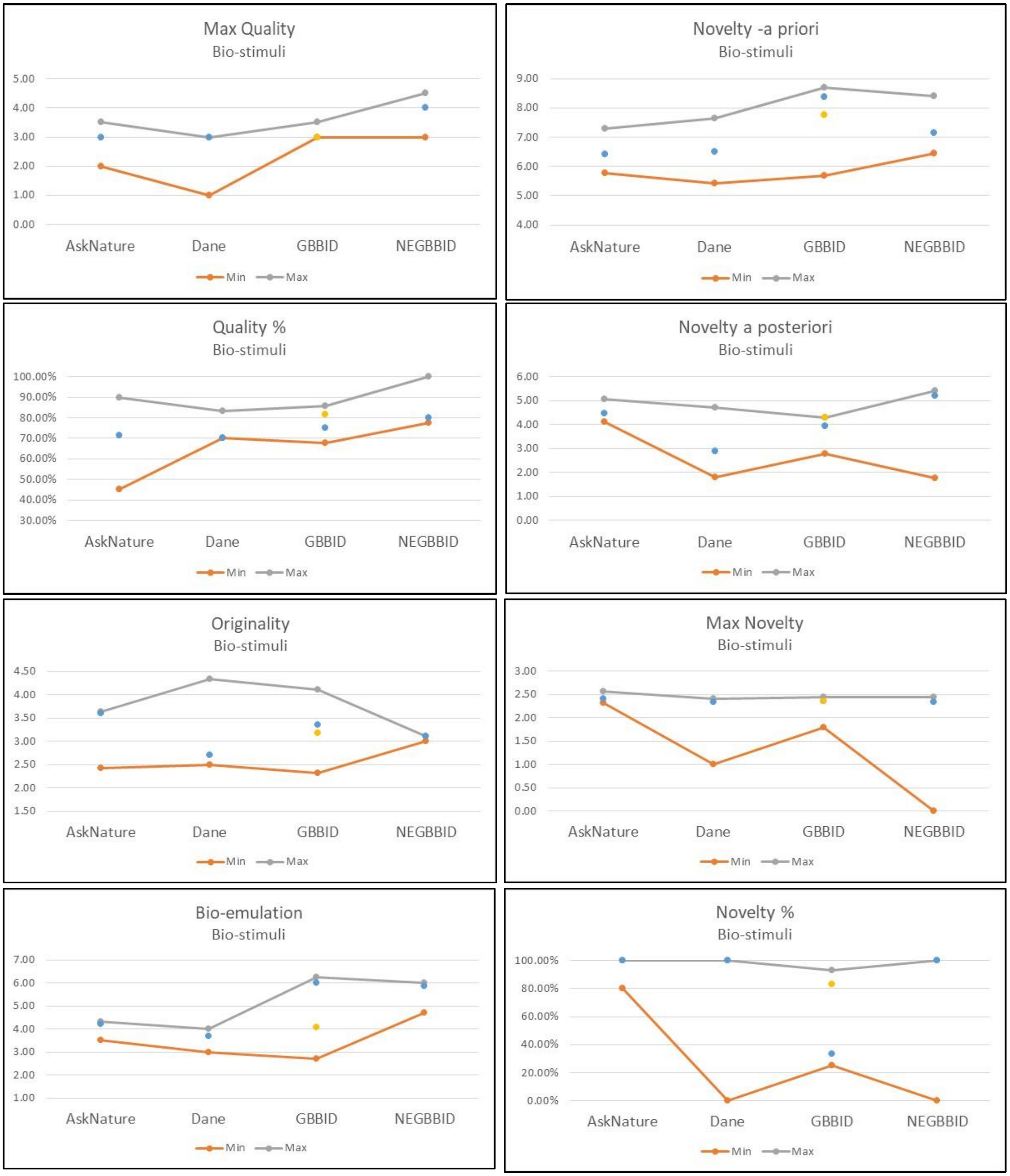



*Figure 7-11: Workshop with engineering students - Metrics for the Biological-stimuli session for groups of treatment – The points in the graphs represent the values of a specific metric within the group of treatment (formed mainly by three teams, so three distinct points per treatment group unless some values coincide - GBBID is represented by four teams). Among the values Min and Max have been highlighted. NE-GBBID seems performing better than other methods for Quality/Max Quality while AskNature in Novelty%.*

### *Comparing No-Stimuli/Biological stimuli sessions*

Even if the problem to be solved was different between the session without stimuli and with biological stimuli, because it was of similar complexity, an analysis of the variance was carried out between the two sessions utilizing the Mann-Whitney U test (Table 7-31) which provided the following results:

| Factor/metric | Quantity | Av. Noventy | Av. Quality | Variety | Max Novelty | Max Quality | Perc. Qual. | Perc. Nov. |
|---|---|---|---|---|---|---|---|---|
| **U** | 79.0 | 61.0 | 73.0 | 62.0 | 62.0 | 64.5 | 75.5 | 57.5 |
| **U critical .01** | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 |
| **U critical .05** | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| | U>Ucrit | U>Ucrit | U>Ucrit | U>Ucrit | U>Ucrit | U>Ucrit | U>Ucrit | U>Ucrit |
| **if U > U critical** the null hypothesis cannot be rejected | | | | | | | | |

*Table 7-31: Results of M-W test on comparison between the sessions with and without stimuli of workshop with engineering students.*

The test reveals that there is no statistically significant difference in the metrics between the two sessions. This is also highlighted in Table 7-32 below comparing the averages of metrics.

| Metric | Session | AskNat | Dane | GBBID | NEGBBID |
|---|---|---|---|---|---|
| **Quantity** | Bio-Stimuli | 5.50 | 4.00 | 5.75 | 4.33 |
| | No-Stimuli | 6.17 | 3.83 | 5.13 | 5.17 |
| | difference% | **-10.8%** | **4.3%** | **12.2%** | **-16.1%** |
| **Novelty** | Bio-Stimuli | 7.71 | 7.19 | 7.01 | 6.42 |
| | No-Stimuli | 7.70 | 6.13 | 6.86 | 7.13 |
| | difference% | **0.1%** | **17.5%** | **2.2%** | **-9.9%** |
| **Quality** | Bio-Stimuli | 0.69 | 0.73 | 0.77 | 0.99 |
| | No-Stimuli | 0.77 | 0.79 | 0.80 | 0.69 |
| | difference% | **-10.9%** | **-8.4%** | **-3.1%** | **43.0%** |
| **Variety** | Bio-Stimuli | 44.17 | 30.00 | 39.38 | 33.33 |
| | No-Stimuli | 47.50 | 26.67 | 23.13 | 39.17 |
| | difference% | **-7.0%** | **12.5%** | **70.3%** | **-14.9%** |
| **Max Nov** | Bio-Stimuli | 2.43 | 1.91 | 2.24 | 1.59 |
| | No-Stimuli | 2.26 | 1.44 | 2.08 | 2.35 |
| | difference% | **7.6%** | **32.4%** | **7.9%** | **-32.4%** |
| **Max Qual** | Bio-Stimuli | 2.83 | 2.33 | 3.13 | 3.83 |
| | No-Stimuli | 2.83 | 2.67 | 2.88 | 3.00 |
| | difference% | **0.0%** | **-12.5%** | **8.7%** | **27.8%** |
| **Percentage Q** | Bio-Stimuli | 68.81% | 74.44% | 77.47% | 85.83% |
| | No-Stimuli | 80.00% | 79.44% | 86.22% | 67.58% |
| | difference% | **-14.0%** | **-6.3%** | **-10.1%** | **27.0%** |
| **Percentage N** | Bio-Stimuli | 93.33% | 66.67% | 58.63% | 66.67% |
| | No-Stimuli | 80.00% | 47.22% | 60.48% | 77.86% |
| | difference% | **16.7%** | **41.2%** | **-3.1%** | **-14.4%** |

*Table 7-32: Workshop with engineering students - Comparison of averages of metrics between sessions with and without stimuli.*

**With (Biological) Stimuli – Solution-Driven session:** Instruction: *generate as much as possible solutions to different problems inspired by the two biological solutions provided.*

Three biological solutions provided in different formats: n.6 (Whale's baleens), n. 8 (Shark's skin) and a new organism, n.9 (Toucan's beak). Formats of biological solutions have been swapped among teams so teams could try different methods from the previous problem-driven sessions.

| **Team n.** | **Format of biological solution in Problem-driven session** | **Format of biological solution in Solution-driven session** | |
|---|---|---|---|
| | | **Whale/Shark** | **Toucan** |
| 1 | GBBID | AskNature | Dane |
| 2* | AskNature | GBBID | GBBID |
| 3 | GBBID | AskNature | Dane |
| 4 | GBBID | AskNature | Dane |
| 5 | GBBID | Dane | AskNature |
| 6 | NE-GBBID | Dane | AskNature |
| 7 | NE-GBBID | Dane | AskNature |
| 8 | SBF-DANE | NE-GBBID | GBBID |
| 9 | SBF-DANE | NE-GBBID | GBBID |
| 10 | SBF-DANE | NE-GBBID | GBBID |
| 11 | AskNature | GBBID | GBBID |
| 12 | AskNature | GBBID | GBBID |
| 13** | NE-GBBID | Dane | AskNature |

*Table 7-33: Formats of three biological solutions utilized by each team during the solution-driven session with engineering students. *Initially 4 people of which 2 left before end of the problem-driven session, **4 people with mixed expertize (from ENEL company)*

At the end of the session, the ideas were collected (see example in Figure 7-12) and rated by the two raters. Both a Mann-Whitney U test and a Kendall-W test confirmed their general agreement in rating:

Mann-Whitney test:

| **Factor/metric** | **Quantity** | **Quality** | **Variety** | **Originality** | **BioEmu.** |
|---|---|---|---|---|---|
| **U** | 82.5 | 60.0 | 80.0 | 63.0 | 71.0 |
| **U critical .01** | 34 | 34 | 34 | 34 | 34 |
| **U critical .05** | 45 | 45 | 45 | 45 | 45 |
| **if U > Ucrit** the null hypothesis cannot be rejected | | | | | |

*Table 7-34: Results of M-W test for solution-driven session of workshop with engineering students*

Kendall W test:

| **Factor/metric** | **Quantity** | **Quality** | **Variety** | **Originality** | **BioEmu.** |
|---|---|---|---|---|---|
| **k** | 13 | 13 | 13 | 13 | 13 |
| **m** | 2 | 2 | 2 | 2 | 2 |
| **W** | 0.919 | 0.791 | 0.884 | 0.764 | 0.766 |
| **TIES CORRECTIONS** | | | | | |
| **W** | 0.934 | 0.800 | 0.891 | 0.770 | 0.801 |
| As W is > 0, the agreement between raters can be confirmed | | | | | |

*Table 7-35: Results of Kendall W test for solution-driven session of workshop with engineering students.*

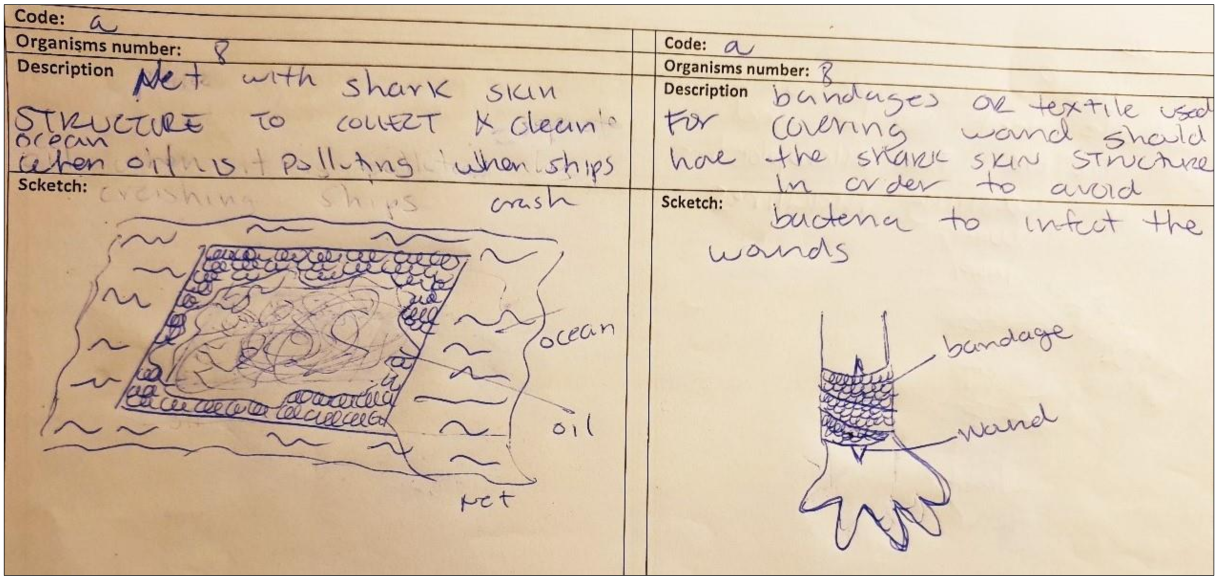



*Figure 7-12: Samples of ideas generated during the Solution-driven session with engineering students using the GB-BID – same biological solution (shark's skin) inspired solution to different problems thanks to the use of sub/extra functions provided by the GB-BID database.*

The scores provided by the raters were averaged:

| Averages Raters | GB/GB | GB/GB | GB/GB | NEGB/GB | NEGB/GB | NEGB/GB | Askn/Dane | Askn/Dane | Askn/Dane | Dane/Askn | Dane/Askn | Dane/Askn | Dane/Askn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | 4.00 | 9.50 | 5.00 | 5.50 | 7.00 | 4.00 | 8.50 | 2.00 | 6.00 | 7.50 | 3.00 | 6.50 | 4.50 |
| Quality | 0.50 | 0.74 | 0.90 | 0.63 | 0.86 | 0.50 | 0.60 | 1.50 | 1.00 | 0.86 | 0.33 | 1.00 | 0.78 |
| Variety | 30.00 | 72.50 | 37.50 | 37.50 | 50.00 | 30.00 | 57.50 | 10.00 | 40.00 | 60.00 | 20.00 | 45.00 | 32.50 |
| Orginality | 1.50 | 3.03 | 2.70 | 2.17 | 2.64 | 3.13 | 3.53 | 1.00 | 2.75 | 2.92 | 2.00 | 3.60 | 2.73 |
| Bio-Emulation | 1.00 | 1.61 | 3.20 | 2.07 | 1.00 | 1.75 | 2.67 | 1.00 | 3.58 | 2.00 | 2.67 | 2.55 | 1.00 |

*Table 7-36: Workshop with engineering students – Solution-driven session with Biological-Stimuli. Metrics of teams within groups of treatment.*

A Kruskal-Wallis test was carried out to assess if there was a statistically significant difference among the metrics calculated for the different groups of treatment (different couples of BID methods).

| | Quantity | Quality | Variety | Originality | BioEmu. |
|---|---|---|---|---|---|
| **H** | 0.071 | 2.043 | 0.132 | 0.484 | 1.060 |
| ***X2*** | 6.984 | 6.984 | 6.984 | 6.984 | 6.984 |
| | X2>H | X2>H | X2>H | X2>H | X2>H |

*Table 7-37: Results of Kruskal-Wallis test for solution driven session of workshop with engineering students. X2 at 5% and (4-1) degrees using K-W table for 4 groups of 3 data each (4,3,3,3)*

The null hypothesis that the groups of treatment do not differ in their performance cannot be rejected. As a consequence it can be stated that there is no difference in effectiveness among the different couples of BID methods tested in any of the metrics calculated.
In the Figure 7-13 charts of metrics as per Table 7-36.

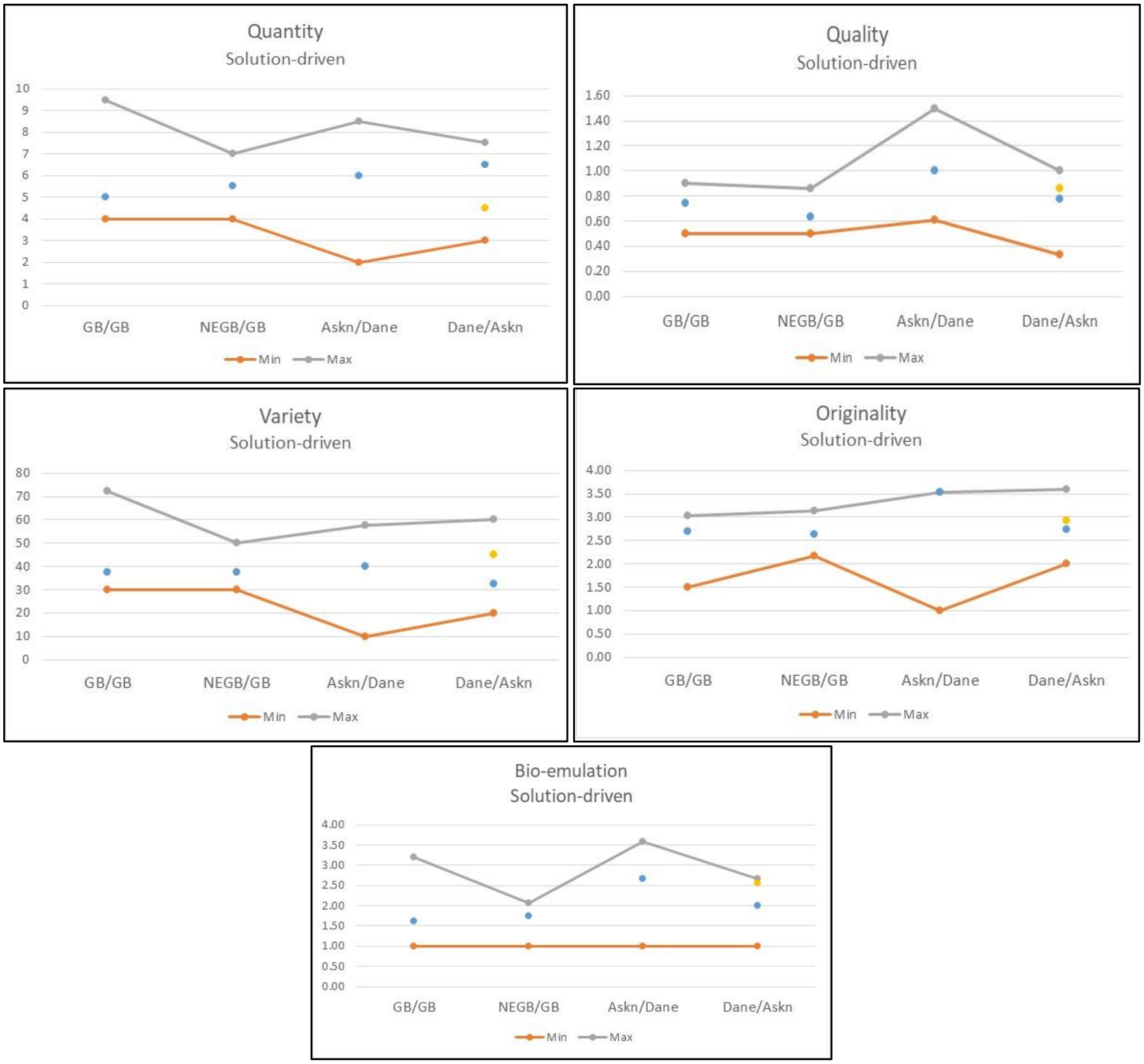



*Figure 7-13: Workshop with engineering students - Metrics in Solution-driven session for couple of BID methods – The points in the graphs represent the values of a specific metric within the group of treatment (formed mainly by three teams, so three distinct points per treatment group unless some values coincide – Dane/Askn group is represented by four teams). Among the values Min and Max have been highlighted*

### *Use of Sub/Extra functions*

The ideas generated were also assessed to measure the use of sub and extra functions provided. Both were only present in the GB-BID sheets (for the Toucan's beak and Shark's skin) but sub-functions also in the DANE method (which does not foreseen extra functions). Below, Table 7-38 highlighting the percentage of ideas generated from the main functions and from the sub/extra functions. Having sub and extra functions allows increasing the number of ideas generated in a solution-driven approach.

| Couple of BID methods utilized by treatment groups | Main functions | Sub/Extra functions | Comments |
|---|---|---|---|
| GBBID/GBBID | 59.1% | 40.9% | Include some extra-function |
| NE-GBBID/GBBID | 66.7% | 33.3% | Include extra-function from GBBID, not from NE-GBBID |
| AskNature/Dane | 50% | 50% | Sub-function derived from DANE |

| | | | |
|---|---|---|---|
| Dane/AskNature | 64% | 36% | Sub-function derived from DANE |

*Table 7-38: Percentage of ideas generated from the main functions and from the sub/extra functions by the treatment groups.*

### *Relevant consideration from the Questionnaire*

The following considerations have been derived from some of the questions replied by participants.

In terms of indicators of applicability of the BID methods, both GBBID and NEGBIBID show slightly better scoring than AskNature and Dane:

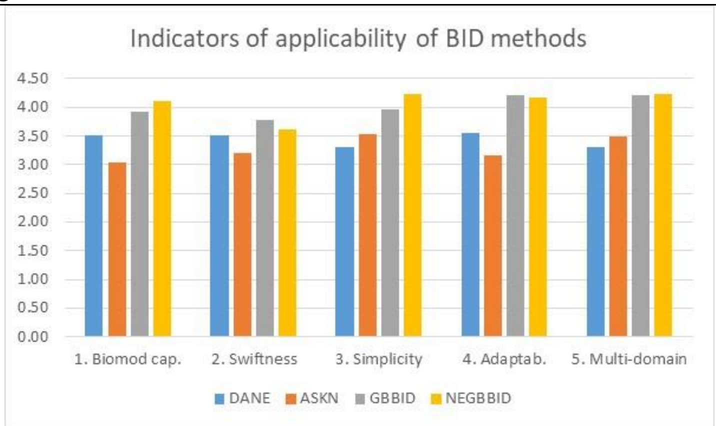



*Figure 7-14: Indicators of applicability of BID methods from questionnaire of workshop with engineering students.*

1. **Biological Modelling capacity**: capacity of the tool to represent biological models in a useful way to stimulate ideation process
2. **Swiftness**: necessary time for getting acquainted with the tool following initial introduction
3. **Simplicity**: perceived complexity of the tool
4. **Adaptability**: suitability of the tool and information provided to explore solutions in other domains
5. **Multi-domain capacity**: suitability of the tool to be used by users with different background

Which is the format of biological information you find more useful for the purpose?

| Score | Frequency | Text | Frequ. | Graphs | Frequ. | Drawing | Frequ. | Photo |
|---|---|---|---|---|---|---|---|---|
| **1** | 7 | 19.44% | 3 | 8.11% | 5 | 13.89% | 5 | 13.51% |
| **2** | 8 | 22.22% | 5 | 13.51% | 7 | 19.44% | 7 | 18.92% |
| **3** | 5 | 13.89% | 8 | 21.62% | 9 | 25.00% | 9 | 24.32% |
| **4** | 9 | 25.00% | 12 | 32.43% | 12 | 33.33% | 10 | 27.03% |
| **5** | 7 | 19.44% | 9 | 24.32% | 3 | 8.33% | 6 | 16.22% |
| | **Total score** | **109** | | **130** | | **109** | | **116** |
| | **Average score** | **3.03** | | **3.51** | | **3.03** | | **3.14** |

*Table 7-39: Scores on preference of formats of biological information. Percentages for each score for each format type (text, graph, drawing, photo), total scores and averages.*

Graphs and diagrams such in the DANE representation scored the highest.

Did your background influence the creative process?

| Score | Freq. | % |
|---|---|---|
| **1** | 1 | 2.70% |
| **2** | 2 | 5.41% |
| **3** | 9 | 24.32% |
| **4** | 20 | 54.05% |
| **5** | 5 | 13.51% |

Did you apply existing technologies to generate ideas?

| Score | Freq. | % |
|---|---|---|
| **1** | 2 | 5.41% |
| **2** | 3 | 8.11% |
| **3** | 11 | 29.73% |
| **4** | 17 | 45.95% |
| **5** | 4 | 10.81% |

*Table 7-40: Percentages of scores on influence of participants background on their creative process*

*Table 7-41: Percentages of scores on use of concepts of existing technology by participants in their creative process*

Most likely due to the engineering background of the participants, both background and application of existing technologies have been considered as playing a role in the generation of ideas.

Were Extracted Design Princ. useful to generate ideas?

| **Score** | Freq. | % |
|---|---|---|
| **1** | 2 | 5.88% |
| **2** | 0 | 0.00% |
| **3** | 7 | 20.59% |
| **4** | 17 | 50.00% |
| **5** | 8 | 23.53% |

*Table 7-42: Percentages of scores on perceived usefulness of provided Extracted Design Principles in the creative process*

Do they conditioned the creative process?

| | Freq. | % |
|---|---|---|
| Yes | 17 | 50.00% |
| No | 17 | 50.00% |

*Table 7-43: Percentages of scores on perception of influence of provided Extracted Design Principles in the creative process of participants*

The Extracted Design Principles already proposed in the GBBID and NE-GBBID, if on one side they were considered useful in generating ideas, on another there was a split between participants in considering them as hampering the creative process.

*Final Considerations*

From the results of this workshop, taking into consideration the profile of the participants and their potential level of motivation in the exercise, the following aspects seem emerging:

- The Kruskal-Wallis test reveals no significant difference in the metrics among the different BID methods, in both problem-driven and solution-driven modality. So none of the methods results to be more effective than the others.
- The broad breath of the problems, selected in order to guarantee a consequent broad breath of solutions, may have played a role in the results. Having selected a more specific problem with more constraints and therefore with a narrower breath for solutions, could have possibly pushed participants in using biological analogies in a more effective way.
- The solution-driven session highlighted the capacity of GB-BID method to stimulate ideas utilizing sub and extra functions (the latter not present in other tested methods).
- In terms of indicators of applicability of the BID methods tested, the questionnaire reveals that GB-BID and NE-GBBID perform better than DANE and AskNature.
- There is no evident preference in the format for biological information, with a slight preference for graphic/diagram format like in the DANE model. This differently from the workshop at Digital Universitas where graphic/diagram format was scored the least.

## 7.5 Ideation Workshop with Knowledge-based experts

In order to test the combination of the Evolutionary Innovation Model and the GB-BID database on separation, the ideal ideation workshop should have involved participants from TIER 3 to TIER 1 of the Separation Technology sector as per section 6.4.

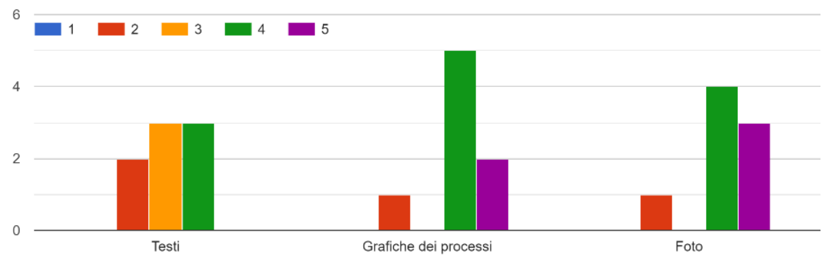
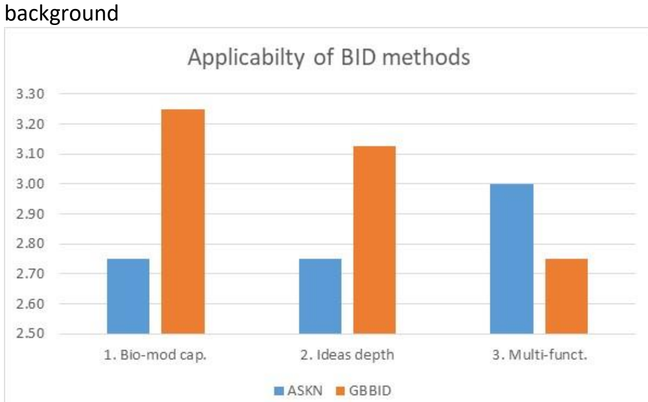
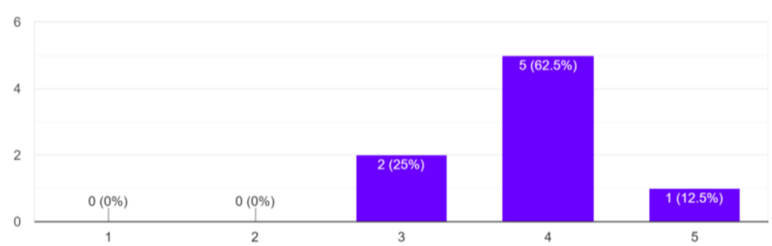
The researcher made several efforts in order to generate opportunity to set up such a workshop:

- On 4/09/2018, the researcher presented a paper on one of the case studies (the Mangrove Still desalination system) to the Desalination for the Environment conference organized by the European Desalination Society (http://www.desline.com/congress/Athens2018/program.html). The presentation allowed generating interest in the audience, formed by representatives of the Separation Technology industrial sub-sector of water desalination, as well as connecting with companies which could have been interested in participating to a BID ideation workshop.
- The researcher, on 23/10/2019, presented a paper on preliminary result of the research (including the case studies) to the Filtech Conference-Exposition 2019 (the largest European fair on the topic of Separation Technology: https://filtech.de/conference/conference-programme-2019). The presentation allowed generating interest in the audience, formed almost exclusively by representatives of the Separation Technology industrial sector, as well as connecting with companies which could have been interested in participating to an BID ideation workshop. Brief interviews with 28 companies were also held during the exposition to explain them about the research and to gather information about the innovation process within the sector.
- The researcher asked the organizers of Filtech 2019 if it was possible to organize the workshop within Filtech. Unfortunately, this opportunity could not materialize.
- Because of the necessity of holding the workshop at the Politecnico di Milano, the researcher contacted 18 companies which operate around Milan among the ones attending Filtech and the Desalination for Environment conference.

Finally, only five companies confirmed their interest in participating to the ideation workshop held on 13/02/2020. Eleven participants attended the workshop of which eight representing the five companies, two from the Department of Chemical Engineering and one from the Department of Mechanical Engineering of the Politecnico di Milano.
Among the companies there were developers of filtering media (technical textile for filtration processes), hydraulic and process filters producers, developers and utilizers of filters in household and industrial appliances. Despite the limited number, it is considered that the companies could be considered representative of the full range from TIER 1 to TIER 3, including clients.
Three teams with three people and one with two people were formed mixing members from the different companies.
The workshop proceeded according to the process described in section 3.3.5.

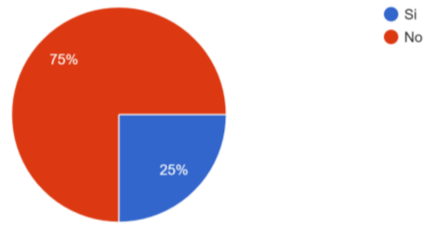
The problem proposed was: *How to remove microplastics before they reach natural water bodies but after they left the water users facilities* (industries, households,etc.).
A range of microplastic dimension was selected by the participants: 30µm-5mm

The teams were left free to start working individually and then discuss ideas within the team. A final idea had to be presented at the end of each session.
From the first session with information from AskNature all the teams decided to work on a single idea. The idea was kept also when they received different inputs from the GB-BID material also because some of the biological solutions found in AskNature were similar to the one provided by the GB-BD but with different depth of information.
A certain disruption was reported when members from teams swapped, as moved members brought new thoughts to their new team which somehow could divert or complement from what already developed.
The goal of the workshop was not to measure ideation metrics but to gather opinion from the participants through a final questionnaire (see Annex 6) which was filled up by all the eight participants from companies. From this, the main results are highlighted in Table 7-44:

| **Replies from the Questionnaire** | **Considerations** |
|---|---|
| *If yes. How was it useful the taxonomy of biological solutions?*<br> | The Taxonomy of biological solutions was useful to 7 on 8 participants. To one participant it allowed to have new ideas and to 4 of them to have an integrated vision of the inspiring principles. |
| *How useful they were the various formats of information to understand the biological models? (5 - very useful, 1 – low usefulness)*<br> | Graphics/drawings and photos have been considered more useful than text for understanding biological models. |
| • Bio/mod. Cap.: capacity of the tool to represent biological models in a useful way to stimulate ideation process<br>• Ideas depth: capacity of the method to generate ideas well formulated and detailed<br>• Multi-functional capacity: suitability of the tool to be used by users with different background<br> | GBBID scored higher than AskNature for capacity to represent biological models and depth of ideas generated. AskNature scored higher in terms of adaptability to different professional backgrounds. |
| *Were the Extracted Design Principles (EDP) of the GBBID useful? (1-low, 5-high)*<br><br>Comments:<br>• They represented a moment for focusing on representation and synthesis of information.<br>• They allowed me to have a deeper knowledge and understanding of the organisms. | The Extracted Design Principles provided by the GBBID are considered largely useful and not hampering the creative process. |

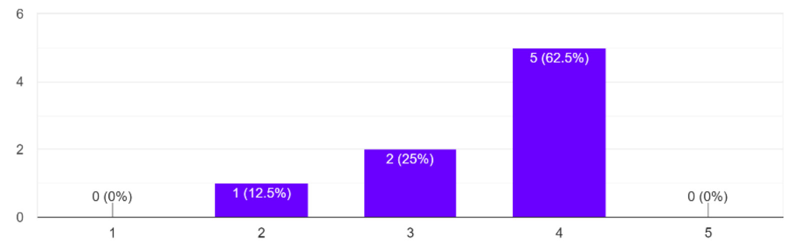
<table>
<tr><th>Replies from the Questionnaire</th><th>Considerations</th></tr>
<tr><td>

*Do you think the EDPs conditioned or hampered your creative process? YES/NO*



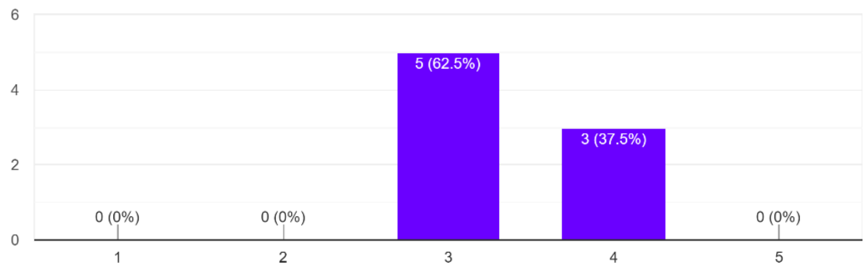

</td><td></td></tr>
<tr><td>

*Did you find useful the information in the "context" fields of the GBBID? (1-low, 5-high)*



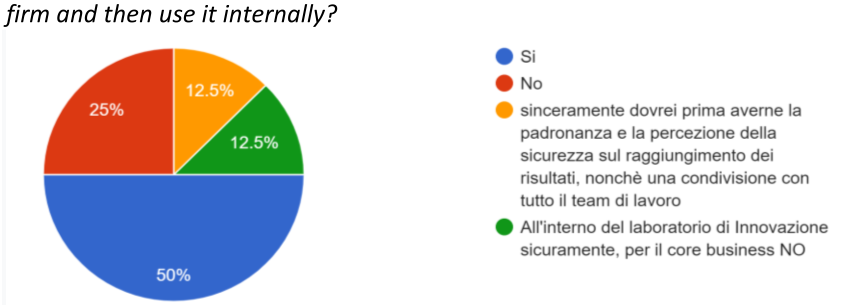

</td><td>Information included in the fields of "context" (ex: "Active/Passive" process, "scale", "Energy" etc.) have been considered rather useful for the ideation process.</td></tr>
<tr><td>

*How much do you think your background influenced the creative process? (1-low, 5-high)*




</td><td>The knowledge-based expertise had a rather relevant influence on the creative process.</td></tr>
<tr><td>

*Would you invest in creating a BID method adapted to the products of your firm and then use it internally?*




If you chose NO, why?

- Perhaps still far from industrial reality in the translation and interpretation phase of the biological phenomena.
- Still rigid towards production systems and technologies currently used.
- Core business products have their own dimension, a BID approach would certainly be interesting for new projects and new markets

</td><td>If there is a positive attitude toward creating a BID method to be used within the firm, its applicability has to be explored further on a case-by-case approach vis-à-vis existing industrial set ups.</td></tr>
<tr><td>

*Would you use the GBBID method in ideation sessions with your suppliers and clients to generate ideas useful to your firm?*

</td><td>There is a positive attitude (6 on 8 participants) toward</td></tr>
</table>

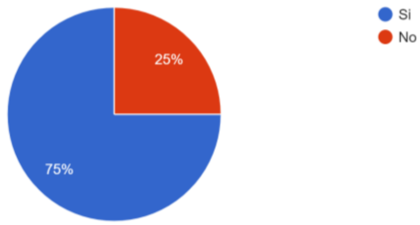
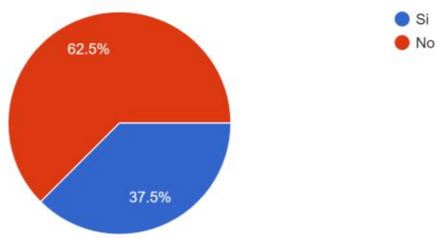
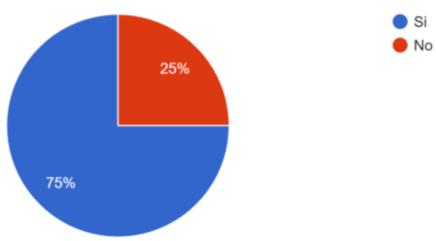
<table>
<tr><th>Replies from the Questionnaire</th><th>Considerations</th></tr>
<tr><td>
If you chose NO, why?<br>• I am not sure that all customers and suppliers would be willing to use such a method (they are not always "open-mind"). I would certainly use this method with selected customers or suppliers. Alternatively I would take the necessary information and apply the method independently/internally to the firm.</td><td>using a BID method within the supply chain.</td></tr>
<tr><td>Will you invest to develop and utilize the GBBID method together with competitors (Open Innovation logic)? Therefore share the costs and the use of the method.<br>
If you chose NO, why? or on what terms would you respond with YES?<br>• Because before investing I should culturally share the approach with the firm’s owners and after evaluate the investments in time and money</td><td>There is a negative attitude towards cooperating with competitors. To be considered that 6 on 8 participants did not cooperate yet with competitors and the 2 firms which did it, it was on the Commercialization phase only. This is also in agreement with the data gathered at Filtech 2019 with 28 companies of which only two of them cooperate with competitors in R&D projects</td></tr>
<tr><td>Will you invest to develop and utilize the GBBID method together with firms of the same macro-sector but not directly competitors?<br>
If you chose NO, why? or on what terms would you respond with YES?<br>• Yes, co-developing a product together and agreeing carefully about Intellectual property</td><td>There is a positive attitude (6 on 8 participants) toward investing in developing the GBBID method with other firms in the macro-sector.</td></tr>
</table>

*Table 7-44: Main results from the questionnaire filled up during the Workshop with Knowledge based experts.*

Additional considerations emerged during a final discussion with the participants:

- It was stressed the fact that biological solutions can be more attractive to take inspiration from than, for instance, patents. This because patents are not necessarily successfully implemented when biological solutions, In their context and at their scale, had past the proof of evolution and are currently utilized successfully by thriving organisms. This can confirm the importance of the Taxonomy of biological solutions which provides not only biological solutions but the ones which occur more frequently in nature and even in different contexts, therefore they could be considered more robust than others and adaptable to more diverse contexts.

- It was suggested to add information on the potential scalability of the biological solutions. This would obviously provide a further and valuable information as technological problems are often at a different scale of the biological solutions. Information on scalability of the processes does not belong to the domain of biology and often not even to the one of engineering. If for some processes, comments on scalability could be provided, for others, specific research should be identified or undertaken. This would obviously increase the cost of the information.
- It was also suggested to introduce more images and descriptive diagrams and drawing to describe the physical/chemical/mechanical principles upon which the biological processes are based.

## 7.6 Conclusion of the Chapter

The refined research question investigated in this chapter was:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

Based on the data gathered and analysed during the ideation workshops held, results are not conclusive to be able to provide a robust affirmative answer to the refined research question. However, the following considerations emerged:

- The GB-BID method allows producing bio-inspired ideas with calculated ideation metrics similar to other BID methods such as AskNature and SBF-DANE.
- According to the ideation metrics calculated, the GB-BID methods did not perform significantly better than other BID methods utilized.
- In terms of perceived applicability, both GBBID and NE-GBBID scored better that DANE and AskNature by both technical and non-technical participants to the workshops.
- The GB-BID method can be successfully used by multi-disciplinary teams including non-technical experts as well as by knowledge-based experts.
- The difficulties in finding participants and the workshops setup might have affected the results. In particular, the high amount of biological information provided, the broad breath of the problems to be solved together with the limited time for the workshops, might have biased the results dampening the potentiality of the GB-BID database for producing better ideation metrics than other methods (in particular AskNature). Further experiments should be conducted with different setup; in particular longer duration of the sessions, more participants and different problem’s complexity.
- The workshop with knowledge-based experts identified the usefulness of adding to the GB-BID Database an indication on the potential for scalability of the biological solution; indication on its applicability at different scales and under different operating conditions.

# 8. TESTING AND VALIDATION - Case Studies on Separation Technology

## 8.1 Generation of Case Studies.

Different case studies have been generated consulting the Guild-Based BID Database for Separation to address problems/design challenges specific to four different levels:

1. **Sector Level**: problems common to all the types of separation technology; for instance a function such as "to prevent clogging of filter".
2. **Sub-sectors Level**: problems specific to sub-sectors of separation technology with functions such as: "to remove particles (or oil) from water" or "to remove particles (or water) from air".
3. **Context-driven Level**: problems specific to a certain context for which a certain technology is often utilized; for instance: "to remove particles of 1 mm diameter from a pressured flow of water in a pipe of 1m diameter".
4. **Across-Sectors Level**: problems specific to a different sector than Separation Technology but which still require utilizing the function "to separate". The sector chosen is the Power Generation sector, sub-sector of High-Voltage Insulators.

The approach followed has been the classic problem-driven approach of every BID method:

1. Identify a problem to be solved in the Separation Technology sector;
2. Re-formulate the problem in biological term ("How would nature do that?");
3. Searching in biology querying the GB-BID Database for biological solutions;
4. Identify the biological solutions and extract design principles;
5. Apply the principles to generate concepts;
6. Prototyping and testing.

## 8.2 Sectoral Case Study – Deep principles of Biological Separation

With the availability of 118 biological entries, it has been possible to initiate the identification of patterns - deep principles - that Nature seems following when dealing with problems of separation. The presence of possible patterns emerged during the process of populating the database. However, once the database was completed, it has been possible to recognize them as patterns assessing their frequency of occurrence within the database.

The patterns identified concern:

- Separation processes;
- Separation mechanisms for specific types of separation process;
- Separating structures;
- Context-driven processes (driven by specific operating conditions)

The researcher identified only some patterns on the basis of his knowledge about separation technologies, but it is not excluded that a more thorough and structured analysis of the database carried out by experts in separation technologies and biologists would most probably reveal more patterns by cross-checking different fields of information of the database with specific queries.

These deep principles recur throughout evolution into several biological systems. Therefore, they embed a certain level of “robustness” in evolutionary terms and could provide indications on which R&D path could be undertaken, and which most likely should not, in order to solve technological problems.

Even if to experts in separation technologies some of the principles may appear obvious and already explored by our design since decades, it should be highlighted that these principles would put on the right track any non-expert in separation technology. They would allow him/her not necessarily to cover the lack of this sectoral knowledge, but possibly to utilize natural solutions to dialogue with sectoral experts providing ideas for research paths and innovative products. In this respect the researcher considers biomimicry not only a powerful mean to achieve innovation, but also and probably even more importantly, as a mean to short-cut the lack of sectoral knowledge and become prepositive in multi-disciplinary design teams.

### 8.2.1 Separation processes

Broad classes of separation process existing in nature have been identified thanks to the information included in the database’s field “separation process”. They have been compared with the separation processes applied in our technology. Taking as a reference the map of separation processes of Figure 6-3, the ones also utilized by biological systems have been highlighted in blue colour in Figure 8-1. To be noticed that all the type of separation (liquid-gas, liquid-solids, etc.) can be found in nature (see examples in Table 8-1).

In particular, Nature seems operating through the following processes: phase change, dialysis, gravity separation, surface cross-flow and dead-end and density separation. From this preliminary analysis, it can be noticed that nature seems not offering any radically new separation process that we did not explore already.

It is striking, but not surprising, the almost complete absence of the use of Depth Filtration in nature when this type of filtration is widely used in our separation technology. Depth filtration with the meaning of using a porous thick medium as filter and then replace it when it is cease to provide the required percentage of retention. This is the typical business strategy of products with a planned obsolescence which necessitate a continuous need for replacements. In nature “planned obsolescence” is present at various scales (for instance cellular replacement or shark’s teeth are continuously produced and replaced) but when the function is not affected by the replacement of the obsolete part. An entire organ is not suddenly replaced but rather its smallest constituents (the cells) are replaced continuously; this to avoid interrupting its function. Due to the importance of the separation function, for feeding and breathing, nature seems opting for structures that do not need to be entirely replaced by interrupting the function risking the life of the organism (though there are exceptions such as the Oikopleura that builds and sheds a “filter house” every 4-6 hours). It is possibly under this perspective that nature could not consider depth filtration a winning strategy; waiting for the porous medium to be clogged and entirely replace it, it would put the organism at risk.

A natural separation process which could be considered similar to a depth filtration is the use of mucus (spread on meshes or surfaces) to trap particles (called is biology *hydrosol filtration*). This is quite frequent in nature, however the mucus traps particles rather superficially and it is continuously produced and either phagogitated as food or expelled.

Other types of separation processes we use that nature seems not using are the ones which involve the use of electric charges or magnetisms as well as cake filtration.

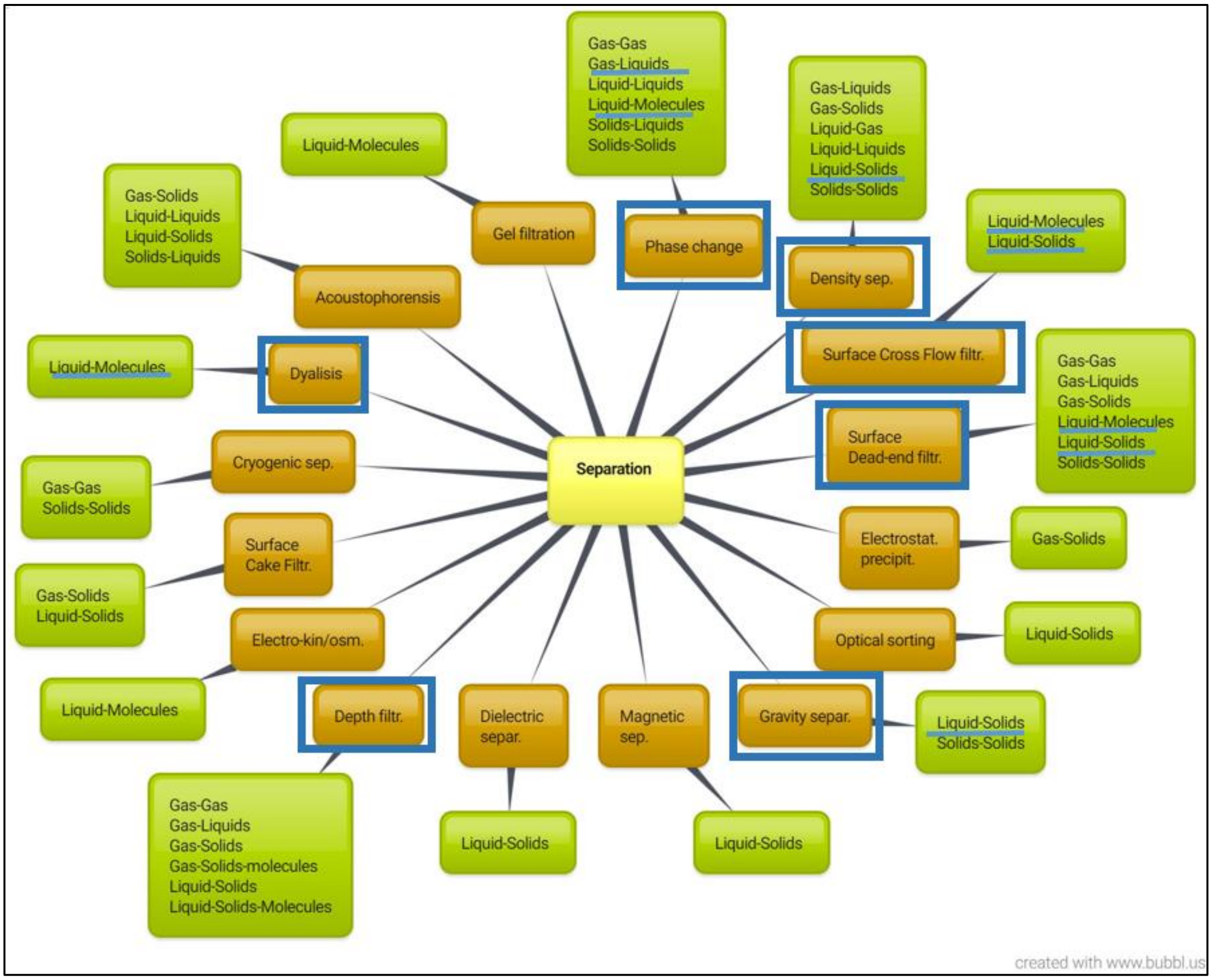



*Figure 8-1: Map of separation processes and types of separation carried out for each process with highlighted (in blue) existing processes in nature*

| Type of Separation | Biological solution |
|---|---|
| Liquid-Solids | Basking Shark's gills trap particles from water |
| Liquid-Liquids | Kidney extracts water and urea from blood |
| Liquid-Molecules | Fish's gills absorb oxygen from water |
| Gas-Liquids | Namibian desert beetle hydrophilic surface condenses air moisture |
| Gas-Solids | Spider web traps particles from air |
| Gas-Gas | Respiratory system extract oxygen from air |
| Solid-Liquids | Plants Roots extract water from soil |
| Solid-Solids | Bacteria extract minerals from rocks |

*Table 8-1: Examples of biological solution for each type of separation process. All but the last one (bacteria) are present both in the GB-BID database and AskNature.*

### *Comparison with AskNature and Find-Structure:*

Consulting AskNature, its biological solutions also included in the GB-BID database, would have provided examples of all the type of separation processes but Solid-Solids. The same result has been achieved consulting Find-Structure's database.

### 8.2.2 Deep Principles - Separation mechanisms and separating structures

Searching for more patterns beyond the type of separation process, the database has been consulted in its fields "Short description of the mechanism" and "separation process". The following broad natural design principles for separation mechanisms and their structures have been identified and listed in Table 8-3 including their frequency of occurrence in the database. In the table also a comparison with related design principles utilized in our separation technologies.

These principles could already inform the design of innovative separation device and related business as well as research paths, which, from the perspective of natural evolution, it may not be fruitful to pursuit. As already mentioned, this is just a first general abstraction process from biological strategies and mechanisms. The expansion of the biological repository with more organisms as well as its utilization in depth could reveal many more design principles and other general patterns of strategies for separation which could be of use in ideation processes.

*Comparison with AskNature and Find-Structure:*

Consulting AskNature till 06/2016, its biological solutions also included in the GB-BID database would have provided examples of all the type separation mechanisms identified (with proportional frequency) but not the one related to *cross-flow filtration* (1) and the one related to the *continuous self-assembling and renewal of clogged meshes* (7). This information was added to the GB-BID database by the researcher following further research into the biological mechanisms. Following a further consultation of AskNature in mid-2019, those mechanisms could be finally identifiable because of the introduction of relevant biological solutions and detailed information in 2017 (Salp feeding system) and 2018 (Baskin shark feeding system).

Consulting *Find-Structure*, none of the deep principles mechanisms above could have been identified as the database does not include enough biological solutions to determine a certain frequency of occurrence of biological mechanisms (unless related to structure-function patterns) and the description of the mechanisms of the biological solutions is not enough detailed to extract certain information. The Find-Structure database contains entries whose function can relate with the function "to separate" but whose associated solution is not necessarily relevant for the sector of Separation Technology. In Table 8-2 an assessment:

| **Function** | **N. of entries** | **Relevance to Separation Technologies** |
|---|---|---|
| Filter | 4 solutions | All relevant and present in the GB-BID database but description of mechanism not detailed |
| Separate | 3 solutions | Not related |
| Remove | 3 solutions | Two are relevant and included in the GB-BID database but description of mechanism not detailed |
| Attach/Detach | 34 solutions | Not all relevant. The relevant one are present in the GB-BID database but description of mechanism not detailed |
| Trap | 4 solutions | One is relevant: penguin's feather trapping air |
| Absorb | 15 solutions | Not related |
| Regulate | 17 solutions | One relevant: ultrafiltration by the mangrove tree roots |

*Table 8-2: Assessment of functions related to "Separate" in Find-Structure and relevance of solutions for Separation Technology*

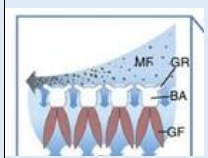
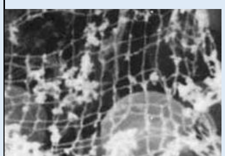
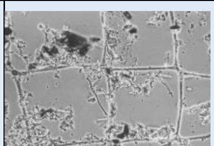
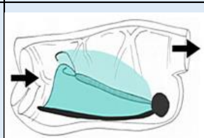
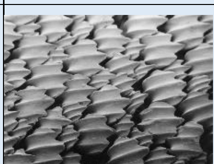
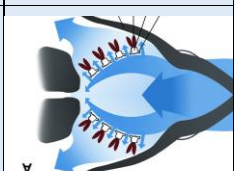
| | | Design Principles for separation of biological systems | Human Design Principles |
|---|---|---|---|
| 1 |  | **Use of Cross-Flow filtration, absent or rare backwashing** (ex: Fish, Basking shark feeding process through gill rakers)<br>Frequency: 10% | Backwashing often needed to unclog filters in surface dead-end filtration |
| 2 |  | **Separate by transforming/changing phase at ambient conditions**.<br>Mainly condensation/evaporation processes and chemical reactions (ex: camel nasal turbinates facilitate air moisture condensation). Frequency: 8% | Phase change (distillation, driers, condensers) with high energy input |
| 3 |  | **Inertial impaction/direct interception/diffusion on mesh fibres**.<br>Sieving is rather a problem as it can damage the mesh. (ex: salps, caddis fly larvae nets)<br>Frequency: 15% | Sieving is a major mechanism of trapping particles |
| 4 |  | **Use of mucus or adhesive substance on meshes or surfaces to withhold particles (hydrosol/hydrogel filtration). Depth filtration but filter media is re-utilized**<br>Mucus that is digested with particles as food<br>Frequency: 12% | Depth filtration (filters need to be regularly replaced/cleaned) |
| 5 |  | **Continuous self-assembling and renewal of clogged meshes** during separation process. Clogged meshes are digested as food. (ex: salps, sea-squirts feeding system)<br>Frequency: 4% | Pre-assembled fixed meshes to be removed or backwashed when clogged |
| 6 |  | **Separation process and flow management via surface morphology** (ex: oleo-phobicity in water of shark's skin, moisture condensation on cacti thorns, wettability regulation of leafs). Frequency: 20% | Rare use of functional surface to separate and manage flows |
| 7 |  | **Use of forms to regulate flows passively**<br>Maintenance of laminar flow via hydrodynamic body shapes and configuration and shapes of channels to manage turbulence. (Ex: Basking shark mouth, fish's body shape). Frequency: 20% | Use of energy to regulate flows |

*Table 8-3: Nature design principles vs human design principles for separation mechanisms and their structures. Highlighted also the frequency of occurrence in the GB-BID database.*

### *Examples of applicability*

To demonstrate the applicability of the above principles as Decision-making/Evaluation tool, the researcher selected two examples in separation processes for seawater desalination:

1. Spacers in Reverse Osmosis (RO) spiral wound membranes;
2. Falling film evaporation.

**1. Problem**: Spiral wound RO filters need *to keep membranes separated* (to allow seawater to flow between them) and *to generate turbulences to avoid concentration polarization*.

**Current solutions**: spacers (polymeric nets) are introduced in spiral wound membranes to carry out the abovementioned functions. Because of their shape, biofouling occurs in "dead spaces" reducing separation efficiency. Feed water pre-treatment is not enough to prevent the problem.

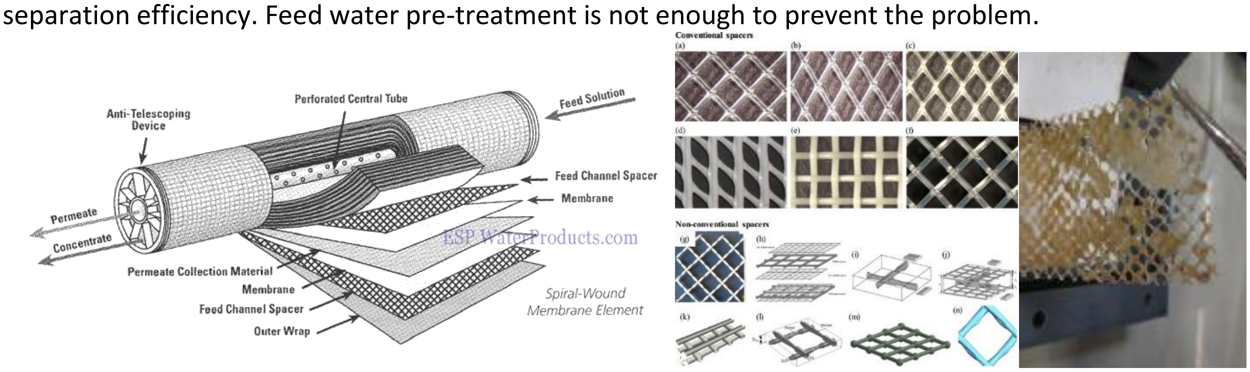



*Figure 8-2: Spiral wound membrane showing spacers (left); different type of shapers (centre); spacer with fouling (right)*

**Function**: *to keep two surfaces separated (of mm) and generate micro turbulences along surfaces*

**The GB-BID Database suggested Design/operative principle**: Querying for keywords such as "*manage liquids*, *on surface*, *passively*" the GB-BID would point at entries providing extracted design principles such as *generating micro turbulences* via surface micro-textures (micro grooves/pillars). One of the macro-principles highlighted in Table 8-3. The same solution could also satisfy the function of keeping two surface separated.

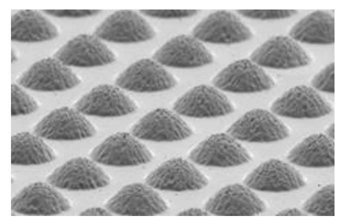


*Figure 8-3: Example of micro-bumps*

**GB-BID inspired solution**: Remove spacers and substitute with micro-pillars

**On-going research**: the researcher found that a rather similar research path is already on-going utilizing "open channel" membrane configurations which do not have "dead spaces" (Pervov, and Matveev 2014)

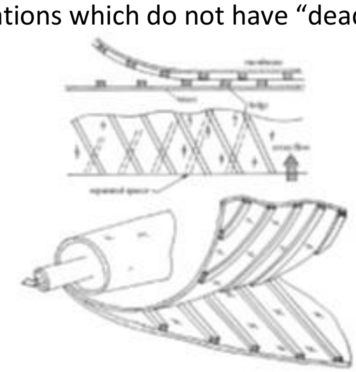
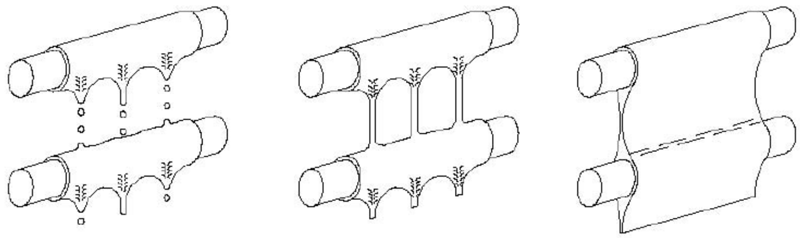


*Figure 8-4: Example of design of open channel membrane*

**2. Problem:** Heat transfer from a horizontal heated tube to liquid falling film has been intensively studied in the recent decades due to its wide applications in industrial processes of the refrigeration, chemical, petroleum refining, and desalination. These advantages are high heat transfer coefficient at small temperature differences, very low pressure drop of the liquid flowing over the tubes, and small quantity of working fluid. To be efficient a uniform thin film of water over the pipes should be produced; scaling should be avoided as well as creating dry spots which would facilitate salt crystallization and scaling. The flow pattern of this falling film as shown in Figure 8-5 below mainly depends on the flow rate, the tube spacing, and the physical properties of the liquid. (Schausberger, Nowak, and Medek 2009)

*Figure 8-5: The idealized inter-tube falling-film modes: (a) the droplet mode; (b) the jet mode; (c) the sheet mode*




**Current solutions:** Circular section pipes at specific distances to increase wettability and therefore reducing risks of dry zones formation. Use of anti-scaling compounds in water.

**The GB-BID database suggested Design/operative principle**: Table 8-3 would point at a principle such as "use forms to regulate flow passively". Consulting the database for sub-action+object such as "move liquids", the description of the specific hydrodynamic streamlined shape of fish could be identified. Furthermore in order to increase wettability of the surfaces, also some entries of the main action+object "repel water" or "extract moisture" could be consulted in order to understand how hydrophilicity/phobicity is produced in nature – again mainly via surface morphology.
Analysing the above the following design principles could be applied:
1. Maintain laminar flow using *oval*/*elliptical shapes* rather than circular and
2. Maintain laminar flow and increase wettability via surface micro-textures (micro grooves/pillars).
The use of elliptical shape compared with a circular one would also increase the surface/volume ration increasing the surface available for heat exchange. The use of micro-texture (such in the case of shark's skin or Namibian desert beetle) may also act as anti-scaling.

**GB-BID inspired solution**: Use oval/elliptical section pipes to maintain thin film and increase heat transfer and apply micro-texture on surfaces to reduce detachment of fluid and increase self-cleaning

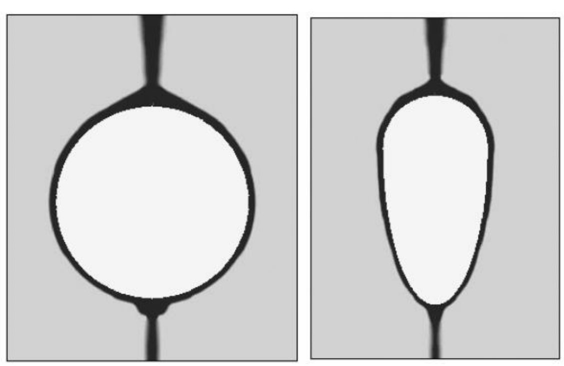


*Figure 8-6: Falling film on circular and oval pipe's section. From (Luo and Pan 2013)*

**On-going research:** the researcher found that moving from circular to elliptical shapes is an already on-going research path which indeed confirms that the overall heat transfer coefficient increases by increasing the ellipticity of the tube, implying that the elliptical tubes possess more advantages over circular tubes in desalination systems. (Jani and Amini 2012; Luo and Pan 2013)

## 8.3 Sub-Sectoral Case Study

A ***Taxonomy of Biological principles on separation*** organized according to major problems of separation expressed in terms of *action, object, object property* and some relevant *process conditions* has been developed. In order to do this, the database has been filtered according to the following keywords:

| Action | Object, Object property | Process Condition |
|---|---|---|
| Separate | Ions/Molecules/gasses (including water, NaCl) | Air; Liquids |
| Extract | Water vapour | Air |
| Attract/Repel | water droplets (rain, fog, dew) | Air |
| Repel | apolar fluids (oil) | Air; Liquids |
| Separate/Filter | Particles (microns) | Liquids; Reynolds number intermediate |
| Separate/Filter | Particles (mm-cm) | Liquids; Reynolds number High (turbulent) |

*Table 8-4: Keywords for filtering the GB-BID database in order to develop the Taxonomy on separation.*

For each of the above problems biological mechanisms have been identified and divided between *Active* and *Passive*. Furthermore the biological mechanisms belonging to these two categories have been subsequently grouped by type of separation process and by mechanism which they have in common.
The mechanisms have been described and their frequency of occurrence (expressed in %), within the specific separation problem they belong to, has been estimated. This frequency has been considered as an indicator of the "robustness" of the biological solution; meaning that its recurrence in nature (in several organisms) could be an indication of the effectiveness of that solution for that specific problem.
The taxonomy usefulness has been further tested in an ideation workshop with knowledge-based experts (see 7.5). In Figure 8-7 an extract of the taxonomy which is fully available in Annex 6.

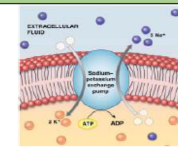
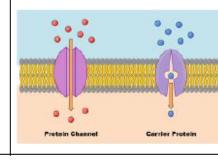
### *Comparison with AskNature:*

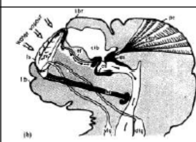
Consulting AskNature till 06/2016, its biological solutions also included in the GB-BID database, would provide the following frequencies of biological functions:

| Function | Entries AskNature | Entries GB-BID |
|---|---|---|
| Separate Ions/Molecules/gasses (including water, NaCl) | 11 | 31 |
| Extract Moisture | 6 | 9 |
| Attract/Repel water droplets (rain, fog, dew) | 10 | 24 |
| Repel apolar fluids (oil) | 0 | 4 |
| Separate/Filter Particles (microns) from fluids, Reynolds number intermediate | 9 | 35 |
| Separate/Filter Particles (mm-cm) from fluids, Reynolds number High | 3 | 8 |

*Table 8-5: Comparison between biological entries from AskNature and GB-BID database retrieved utilizing same keywords*

To be noticed that AskNature does not list any biological solution related to repel apolar fluids. On the other hand it provide biological solutions for all other biological functions (even if without richness of details on the object of the function and its properties).

| Function | Active/Passive process | Processes | Biological Mechanism | Some details | Some Champions | Frequency/ "Robustness" | Pictures |
|---|---|---|---|---|---|---|---|
| **Separate (filter/exchange) Ions/Molecules/gasses** (including water, NaCl)<br>Gas-Gas separation<br>Liquid-Gas separation | **Active**<br>Adenosine triphosphate (ATP)<br>Electrochemical gradients | Active transport (against concentration gradient, primary and secondary) through membrane | Sodium-Potassium pump (enzime).<br>Compartmentalization (directing molecules in dedicated vacuols). | Intra-extracellular environment.<br>Different process depending also on Ions concentrations.<br>Processes activated by concentration, voltage, light, mechanical stresses | Cells membrane<br>Osmoregulator organisms (gills, kidneys)<br>Seagulls salt glands<br>Mangroves roots and leaves | 93.5% |  |
| | **Passive**<br>Electrochemical/Concentration/hydrostratic/osmotic gradients | Passive transport through membrane: simple diffusion, facilitated diffusion, filtration, and osmosis | Ions channels (Proteins channels and proteins carriers)<br>Osmolites compounds | Intra-extracellular environment.<br>Different process depending also on Ions concentrations.<br>Processes activated by concentration, voltage, light, mechanical stresses | Cells membrane<br>Aquaporins | 6.5% |  |

| Function | Active/Passive process | Processes | Biological Mechanism | Some details | Some Champions | Frequency/ "Robustness" | Pictures |
|---|---|---|---|---|---|---|---|
| **Extract moisture**<br>Gas-Gas separation | **Active**<br>Dynamic pressure gradient (breathing)<br>ATP<br>**Passive:**<br>hygroscopic compound | Phase change via structure and hygroscopic compounds | Convoluted 3D turbinates which maximize surface/volume rations and create useful turbulences.<br>Desaturation of air passing over hygroscopic compound spread on the turbinates | In almost saturated air (75/90%) | Camel nose<br>Elephant seal nose<br>Saiga | 66.7% |  |
| | | Phase change via hyperosmotic/hygroscopic compounds | Expose hyperosmitic/hygroscopic compounds to the external humidity to collect water | In almost saturated air (75/90%) | Cockroach mouth<br>Tick mouth<br>Nolama Mollis leaf | 33.3% |  |

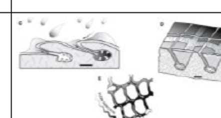
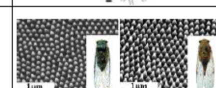
| Function | Active/Passive process | Processes | Biological Mechanism | Some details | Some Champions | Frequency/ "Robustness" | Pictures |
|---|---|---|---|---|---|---|---|
| **Attract/Repel water droplets (rain, fog, dew)**<br>Gas-Liquid separation<br>Solid-Liquid separation<br>Liquid-Liquid separation | **Passive**<br>Surface energy/roughness<br>Laplace pressure gradient | Coalescence of droplets/Hydrophilicity | Nano/micro grooves, ridges and/or hyerarchical structures on surfaces (pillars) gathering and moving fluids | Near-random array of bumps 0.5–1.5 mm apart, each about 0.5 mm in diameter. The peaks of these bumps (about 100µm in diameter) are hydrophilic, whereas the troughs are superhydrophobic by virtue of microstructure consisting of flattened hemispheres, 10 µm in diameter and arranged in a regular hexagonal array (Namibian Desert Beetle). | Namibian Beetle cuticle<br>Desert plant in general (Cacti spines, Tillandsia leaf)<br>Cribellate spider net | 33.3% |  |
| | | Capillarity | Micro channels absorbing and moving fluids | Capillaries between 27–327 µm in width, a depth from 36 to 63 µm (Thorny devil) | Thorny devil skin, Orchids roots, Bromeliades leaf (trichomes) | 12.5% |  |
| | | Hydrophobicity | Nano/micro hyerarchical structures on flat surfaces repelling and moving fluids | Ex: Cicada wing: Conical pillar: ⌀= 85 nm, S= 90 nm, h= 462 nm<br>Pillar density 42 per 1/10000 µm2 | Lotus leaf, Birds feathers, Cicada wing, Collembola cuticle | 50.0% |  |
| | **Active /Passive**<br>Metabolism | Physical barrier gathering fog | Building structures intercepting fog-bearing winds<br>Optimized exposition of fog catching fibres structures | Trenches in sand with shoulders of few millimeters high perpendicular to wind direction.(beetle)<br>Disposition of bushes in banded patterns along the slope of the terrain to maximize interception | Flying saucer thench beetle | 4.2% |  |

*Figure 8-7: Extract from the Taxonomy of Biological principles on separation:*

## 8.4 Context-driven Case Studies

Two different bio-inspired products have been generated deriving from two different context-driven problems (seawater desalination and anti-bacterial surfaces). They have been brought forward to different level of development in academic and industrial environment.

### 8.4.1 The Mangrove Still – Seawater Desalination System

**Problem:** *How to desalinate saline water in drylands and use the produced water to activate land regeneration practices?*

Below, the process of problem-driven approach that has been followed which considers the consultation of the GB-BID database on separation to carry out the biological search. The process was iterative, moving from a broader and systemic perspective of the problem to a technological one:

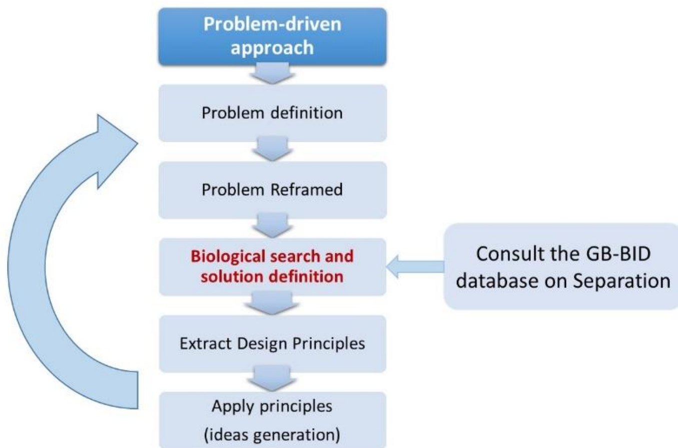



*Figure 8-8: Problem-driven approach followed which led to the Mangrove Still ideation. The circular arrow represents the iterative process followed.*

*Problem Definition*

The problem to be addressed utilizing the GB-BID method started from the decision of the researcher, in 2015, to participate to the Biomimicry Global Design Challenge that the Biomimicry Institute (biomimicry.org) launches every year to address global challenges of humanity and calls for bio-inspired solutions from innovators from all around the World. In 2015 the Challenge was about Food Systems in general. How to make them more sustainable in terms of effectiveness, efficiency and impact on the planet. The researcher decided to participate to the challenge utilizing the information that already populated the GB-BID database on Separation.

In order to converge toward a narrower, more focused problem within the broader context of Food System, a problem related to separation technologies, the researcher decided to address the problem of land degradation in arid semi-arid areas of the World.

*Short background about the context:*

Land degradation affects directly the productivity of important crops, contributing to major losses in agricultural food production and affecting agricultural sustainability. In 2012, the UNCCD (UN Convention to Combat Desertification) proposed a new ambitious target aimed at achieving a land degradation neutral

world by 2030 (UNCSD, 2012). This can be achieved by scaling up sustainable forest and land management to avoid the degradation of natural capital or by offsetting land degradation through land restoration.
In drylands (where FAO estimates that 44% of food production is made) land degradation is caused by wind erosion and salinization, loss of organic substance, sealing and compaction exacerbated by bad land management practices with consequent loss of productive soil and vegetation. In these regions, soil conservation and rehabilitation are essential for sustainable agriculture and improvement of dryland ecosystems. *Revegetation* is one of the most effective means to control soil degradation and to rehabilitate degraded lands. Therefore a crucial element to regenerate soils is *to restore or increase their water content so as to assist sustainable revegetation practices* by improving the structure of these soils and reduce rain water run-off. *Once the soil reaches a minimum level of water and nutrients, revegetation could start using model of succession of plants* (permaculture.org, n.d.). In general, the progressive increase of organic matter will influence the physical conditions of a soil in several ways: plant residues that cover the soil surface will protect the soil from sealing and crusting by raindrop impact; roots of plants will further increase rainwater infiltration. Plants adapted to arid lands (*Xerophites*) could be used whose physiological and morphological features will help trapping air moisture and soil macrofaunal activity (i.e.: earthworms) will further increase soil porosity and organic content.(FAO, n.d.)
In drylands fresh water is scarce. Depending on specific locations there could be some amount of fresh water available periodically as surface water, rare rainfalls and air moisture, but their low amount and unpredictability, complemented by a soil already lacking of organic matter, do not allow natural revegetation processes (Maliva and Missimer 2012). Sustainable Land Management practices exist which can be applied in order to restore soil productivity as well as preserving it. However these practices need a certain continuous among of fresh water to be activated
If in drylands fresh water is scarce, in many of them there is abundance of saline water ( Figure 8-9); either because they are located in seawater coastal areas or because of the presence of salty lakes and brackish groundwater.

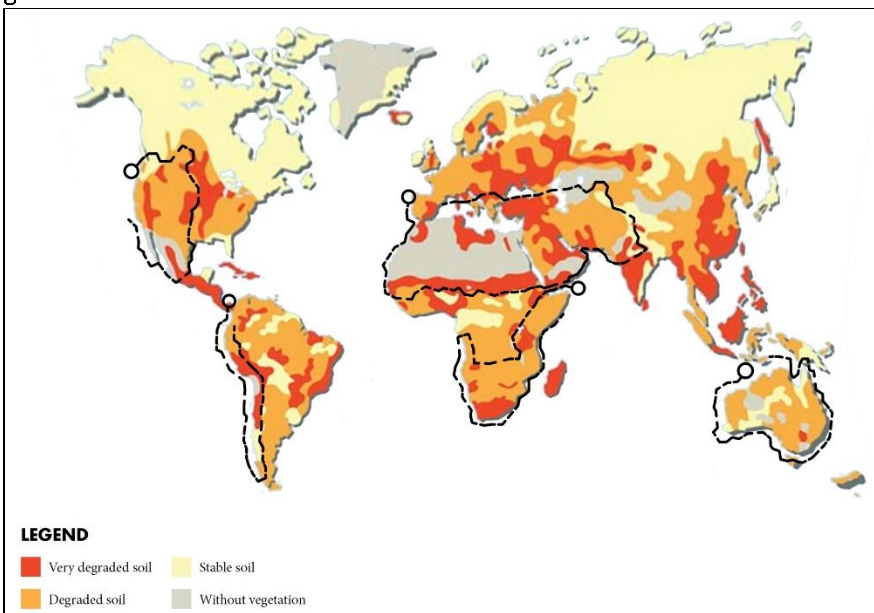



*Figure 8-9: Global Soil Degradation map. From GRID Arendal: www.grida.no/resources/5507*

*Black dashed lines indicate areas with access and abundance of saline water either seawater, salt lakes and brackish groundwater.*

The saline water however needs to be desalinated and transported for different uses. Depending on specific locations there could be additional amount of fresh water available as surface and groundwater, rainfalls and air moisture. These resources are however limited and unpredictable so that they might not guarantee the daily minimum water demand for basic needs and productive activity of coastal communities unless complex and expensive systems for gathering and storing would be set up (for instance through

technologies such as dams, rain harvesters, artificial aquifers, fog catchers etc..) (Maliva and Missimer 2012) with, sometimes, detrimental effects to the local ecosystems.
In high income arid seawater coastal communities - such in the Middle East Countries - desalination is still considered the best option to satisfy a constant, large and, if needed, growing water demand for drinking water, water sanitation and industrial/productive activities. This is also true especially when existing coastal fresh water resources have been compromised (due to over-exploitation and saline intrusion) and costs for recovery would be higher than investing in desalination. A number of suitable technologies are available to provide desalinated water, but costs are still too high to justify the use of this water for agriculture; let alone for regenerating degraded soils.
The use of desalination technology by poor communities of rural and remote areas of Developing Countries is however still limited by the following factors:

- High capital expense for infrastructure. High-energy demand and dependence on fossil fuels.
- Lack of accessible spare parts, consumables and M&O skills.
- Lack of modularity and capacity for decentralization of existing technologies.

For instance, as a general reference, small mobile Reverse Osmosis (RO) desalination units producing around 5 $m^3$/day can cost around 10.000 $ (without considering opex costs) and the cost for produced water can reach more than 10$/$m^3$ (0,01$/L), investment and costs still too high to be afforded by poor communities unless heavily subsidized (Karagiannis and Soldatos 2008).
The cheapest desalination technology available in terms of investment and water cost is the solar still. Solar still units have been already used for desalinating seawater on a small scale for families or small villages in developing countries and in remote islands where solar energy and low cost or donated labour is abundant, but electricity or access to cheap fossil fuel is not. Several suppliers are now offering ready-made units, and the typical cost of a system capable of supplying 10L/day is around $750. If the solar still is built with local material and using local labour, the cost can drop to 200-300$ (excluding costs for pumping seawater and distribution). This technology, modular, could be multiplied so as to provide water to an expanding community (Kabeel, Hamed, and El-Agouz 2010).

### *Problem reframed and Biological Search consulting the GB-BID Database for Separation*

The initial problem was therefore re-framed or "biologized" in order to undertake a biological search. Questions such as "How does nature desalinate?" and "How does nature remove/filter ions/molecules/gasses?" have been considered. Using these keywords to consult the GB-BID database filtering the fields "main action" and "object", it produced the following list of organisms:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Environmental condition |
|---|---|---|---|---|---|
| **Osmoconformers** | **Osmoregulation system** | Separate | ions/molecules | Water | Seawater |
| **Cell** | **Cellular membrane** | Filter | ions/molecules | Water/Plasma | biological tissues |
| **Euryhaline** | **Osmoregulation system** | Separate | ions/molecules | Water | Seawater/Fresh water |
| **Sharks** | **Gills** | Filter | ions | Water | Seawater |
| **Humans** | **Digestive systems** | Filter | molecules | Food | |
| **Tenia Taeworms** | **Feeding system** | Filter | molecules | Water/Food | Digestive system |
| **Insects** | **Respiratory system** | Extract | ions/gasses | air | Various terrestrial/aquatic |
| **Shark** | **Digestive systems** | Extract | molecules | Water | Seawater |
| **Hyper-regulators** | **Osmoregulation system** | Separate | ions/molecules | Water | Seawater |

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Environmental condition |
|---|---|---|---|---|---|
| **Hypo-regulators** | **Osmoregulation system** | Separate | ions/molecules | Water | Fresh water |
| **Brine Shrimp (Artemia)** | **Osmoregulation system** | Separate | ions | Water | Seawater |
| **Vertebrates** | **Kidneys - renal filtration - osmoregulation** | Separate | ions/water | Blood | Biological body |
| **Salt tolerant plants Halophites** | **Root/tissues** | Filter | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Tissues** | Dilute | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Tissues** | Exclude | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Salt glands** | Concentrate | ions | Water (in soil) | Soil with saline water content |
| **Desert Iguana** | **Respiratory system - Salt glands** | Concentrate | ions | Water/air | Desert (California) |
| **Galapagos marine Iguana** | **Respiratory system - Salt glands** | Concentrate | ions | Water/air | Seawater coastal area |
| **Pengiuns, Seagulls** | **Respiratory system - Salt glands** | Concentrate | ions | Water/air | Seawater coastal area |
| **Mangrove (Rhizophora)** | **Root** | Exclude | ions | Water | Seawater/estuary |
| **Mangrove (avicennia)** | **Leaf** | Concentrate | ions | Water | Seawater/estuary |
| **Salicornia** | **Plant tissues** | Dilute | ions | Water | Seawater/estuary |
| **Tubeworms** | **Housing** | Extract | ions | Water | Seawater |
| **Teleostei, Cyprinidae** | **Gills** | Filter | particles/ions | Water | Seawater/Fresh water |
| **Cell** | **Cellular membrane** | Trap | particles/liquids/molecules | Water/Plasma | biological tissues |
| **Cell** | **Cellular membrane** | Expel/Excrete | particles/molecules | Water/Plasma | biological tissues |

*Table 8-6: Result from filtering the GB-BID database in the fields "main action" and "object" using keywords: remove/filter - ions/molecules/gasses.*

A parallel search was carried out in AskNature. Exploring AskNature using single or multiple keywords including the function or its synonymous rather than aiming at searching the main function in the Functional Taxonomy allows a greater variety of organisms and strategies to be selected. If this, on one hand, expands the amount and gradient of biological analogies to be explored (from close to far analogies) possibly generating more novel solutions, on the other it increases the time spent in removing non relevant analogies.

To be noticed that using keywords such as "desalinate" or "separate"/"filter" combined with "ions"/"molecules" in AskNature it would have not been possible to retrieve many relevant biological solutions based on the function AND its object as in the GB-BID database. For instance, regarding the function "to desalinate", only the Mangrove tree is identified by AskNature. Introducing non-function keywords but already known biological solutions (for instance "salt gland") it produced results more similar to the GB-BID database (Figure 8-10). Utilizing just the keywords for the function's object such as "salt" or "ions" or "molecules", it would have been possible to identify the same entries of the GB-BID database only after a screening among apparently irrelevant biological solutions.

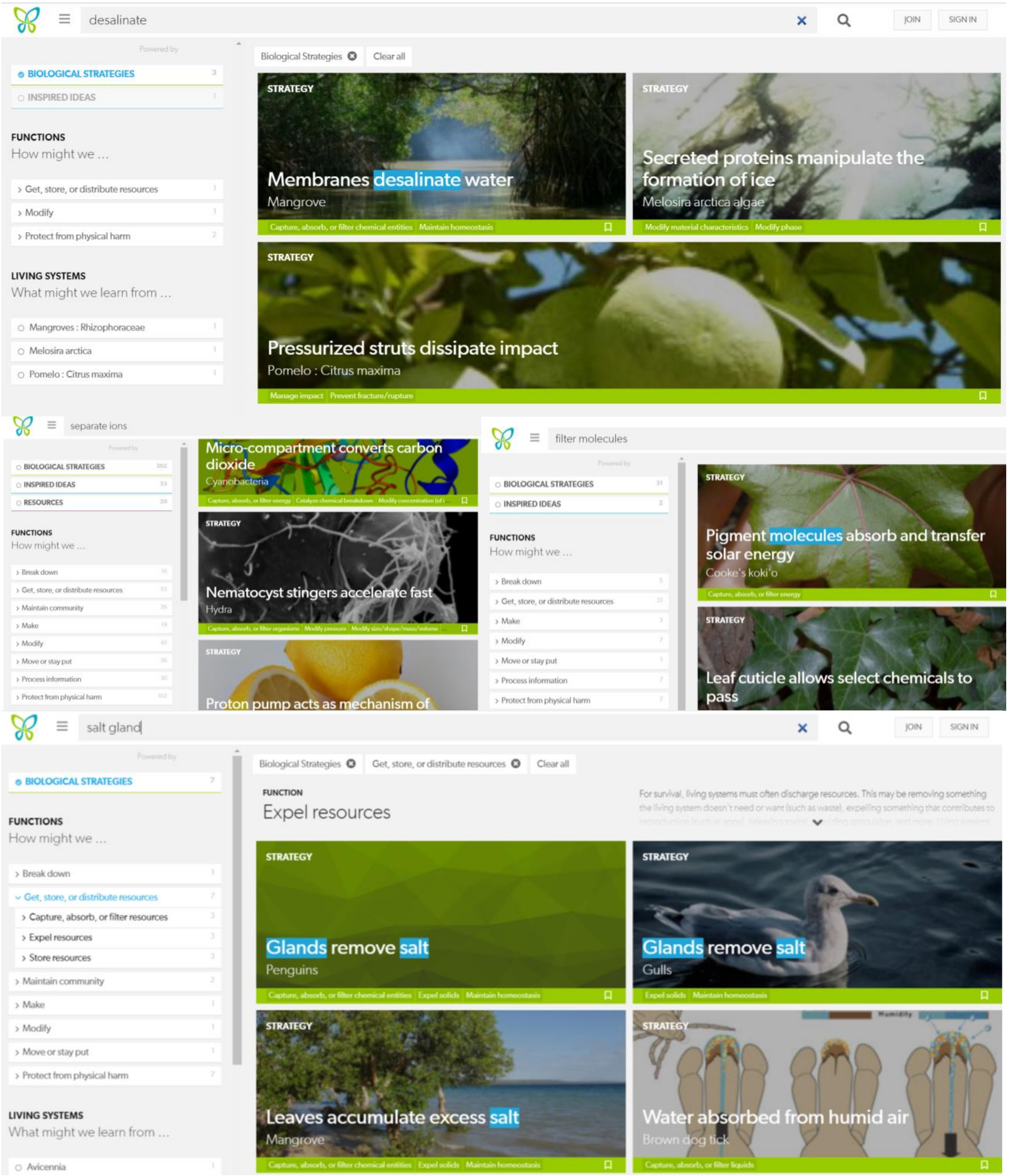



*Figure 8-10: some screen-shots from the consultation of AskNature for keywords such as "desalinate" or "separate"/"filter" combined with "ions"/"molecules" and "salt gland".*

If the organisms and strategies selected from the GB-BID database provided insight on desalination processes, the selection was still too broad as the strategies were not all contextually relevant. Having added to the challenge a specific context: "…*in drylands to regenerate degraded land*" the selection as per

Table 8-6 was further narrowed to the following organisms which operate in similar contexts to the challenge:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Environmental condition |
|---|---|---|---|---|---|
| **Salt tolerant plants Halophites** | **Root/tissues** | Filter | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Tissues** | Dilute | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Tissues** | Exclude | ions | Water (in soil) | Soil with saline water content |
| **Salt tolerant plants Halophites** | **Salt glands** | Concentrate | ions | Water (in soil) | Soil with saline water content |
| **Mangrove (Rhizophora)** | **Root** | Exclude | ions | Water | Seawater/estuary coastal areas |
| **Mangrove (avicennia)** | **Leaf** | Concentrate | ions | Water | Seawater/estuary coastal areas |
| **Salicornia** | **Plant tissues** | Dilute | ions | Water | Seawater/estuary coastal areas |

*Table 8-7: Narrowing the results of Table 8-6 considering Environmental Conditions relevant to the problem.*

This refined list suggested to undertake an assessment of the context within which the organisms survive and thrive to understand their role/function within the ecosystem they are integrated in. More than exploring the question: "HOW do they desalinate saline water?" it was consider relevant to first answer the question "WHY do they desalinate water?". This provided relevant insight for the solution finally pursued. All the organisms selected grow in seawater coastal ecosystems such as Mangrove Ecosystem and Salt Marshes. Therefore, a further understanding on how these ecosystems develop was carried out. Below a brief summary of the investigation:

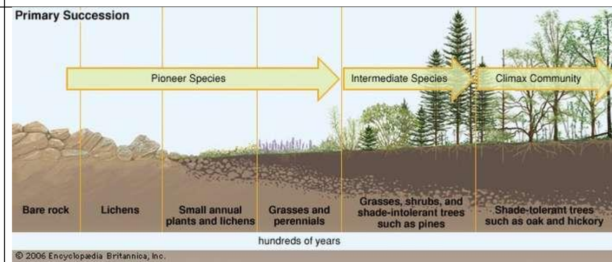
**The Mangrove Ecosystem (or *Mangal*)**

Mangroves are salt-tolerant forest ecosystems found mainly in the tropical and subtropical intertidal regions of the world. They grow along protected sedimentary shores especially in tidal lagoons, embayment and estuaries. They also can grow far inland, but never isolated from the sea. The Mangal is a broad domain encompassing the entire biotic community comprising of individual plant species, associated microbes (like bacteria and fungi) and animals. The Mangal is a highly productive ecosystem despite it is generally nutrient deficient especially in nitrogen and phosphorus, with productivity about 20 times more than the average oceanic production. Intense and diverse microbial activity in mangroves, including Nitrogen- fixing and phosphate-solubilizing microorganisms, is responsible for retaining the scarce nutrients within the system, and that restoration of these tropical ecosystems depends on the health of the microbial benthic communities and conservation of their geochemical environment.(Faridah-Hanum et al. 2014; Parida and Jha 2010; Mitra 2013)

*Figure 8-11:The Mangrove Ecosystem and the Avicennia tree.*

**Salt Marches**

Salt marshes are important transitional habitat between the ocean and the land; they are estuaries where fresh and salt water mix. Salt marsh plants are salt tolerant (halophytes – e.g. *Salicornia*) and adapted to water levels that fluctuate with the tide. Tides carry in nutrients that stimulate plant growth in the marsh and carry out organic material that feeds fish and other coastal organisms. Over time, salt marshes accumulate organic material, forming into a dense layer called peat. Like Mangrove, Salt marshes are among the

| | |
|---|---|
| most productive ecosystems on earth. Salt marshes can be extremely difficult places to survive because of wide daily fluctuations in salinity, water, temperature, and oxygen. Few plants have evolved adaptations to cope with the extreme conditions of salt marshes[i]. When sediment supply is sufficient, salt marsh vegetation can accumulate extensive amounts of fine-grained sediment, which can result in the formation of a salt marsh plateau.(Boorman 1999) | *Figure 8-12: The Salt Marshes Ecosystem and Salicornia.* |
| **Briefly about Ecosystem Succession:**<br>Both Mangal and Salt Marshes can be described in terms of phases of development which include **Pioneer species** (e.g. *Avicennia* for Mangroves and *Salicornia* for Salt Marshes), which are the first to colonize empty ecological niches or previously disrupted ecosystems, beginning a chain of **Ecological Successions** which concerns the gradual process where one community changes its environment so that it is replaced by another, which will ultimately lead to a more biodiverse steady-state ecosystem, the **Climax**.(Mitra 2013) | <br>*Figure 8-13: Phases of an ecosystem development. Enc. Britannica* |

From the analysis of the ecosystems above the main considerations emerged:

- From an ecological perspective, mangroves and salt marshes are unique and significant ecosystems. They support a diverse range of organisms (plants, animals, bacteria and fungi). In fact these plants have been so successful in their development that are among the most productive natural systems found throughout the world.
- Both ecosystems have *pioneer species* (e.g. *Avicennia* for Mangrove and *Salicornia* for Salt Marshes) which are adapted to high saline environment. They are the first species to colonize a high salinity coastal environment and represent therefore the initial stage of the upcoming complex ecosystem. Thanks to their adaptation, *they start creating conditions conducive to other species to appear and survive.* They kick start a progressively self-sustaining process of collection of nutrients and water (through trapping of rare rainfalls, increase air moisture and its collection, reduce evaporation via shading, etc. ) so as to allow other species to appear in a process of succession and zonation which will finally form a mature ecosystem.
- *In coastal terrestrial ecosystems desalination is only one element of an integrated water resources management, however it seems a crucial one, the starting strategy upon which other natural strategies to get fresh water would build upon.*

### *Extracting Design Principles*

From the considerations above the researcher formulated that *a desalination process could be indeed the first element to be considered in seawater coastal areas in order to obtain fresh water where it is not available. However, in medium-long term, it has not to be considered the only strategy, but rather the starting one* which:

- Will help the formation of fertile soils and initial growth of plants with consequent changes in soil texture and microclimate and increased capacity of the building ecosystem to access, generate and store fresh water.
- Will allow local communities starting generating food and income from agriculture.

Therefore, the following broad design strategy was extracted which could solve the initial challenge:

*A financially viable desalination process that allows desalinating and distributing enough fresh water to kick start a process of land productivity (re)generation which progressively generate conditions conducive to other alternative water resources to become accessible.*

### *Applying the Design principles*

Is there an already existing desalination technology which could be improved as it already (at least partially) complies with the above strategy? According to the investigation carried out in the Problem Identification phase the researcher considered the *Solar Still* as the most suitable technology.

### *Reiterated Problem Definition - Solar Still and its applicability*

Therefore the BID process was re-iterated in order to improve the design of the solar still and the following new *sub-challenge* was defined: ***How to improve the Solar Still so as to make it suitable to tackle the main challenge?***

Different designs for Solar Still have been developed and tested in the last thirty years (a categorization in Figure 8-14) in order to increase their efficiency (Manchanda and Kumar 2015). Many of them remain at experimental level because of the complexity of their design or costs not affordable by poor communities. Few have been commercialized but sold at high prices (100-600$/m$^2$) and mainly utilized in gardening by environmentally conscious people. To maximize its yield (L/day/m$^2$ of distilled water), a solar still has *to optimize the evaporation/condensation process*.

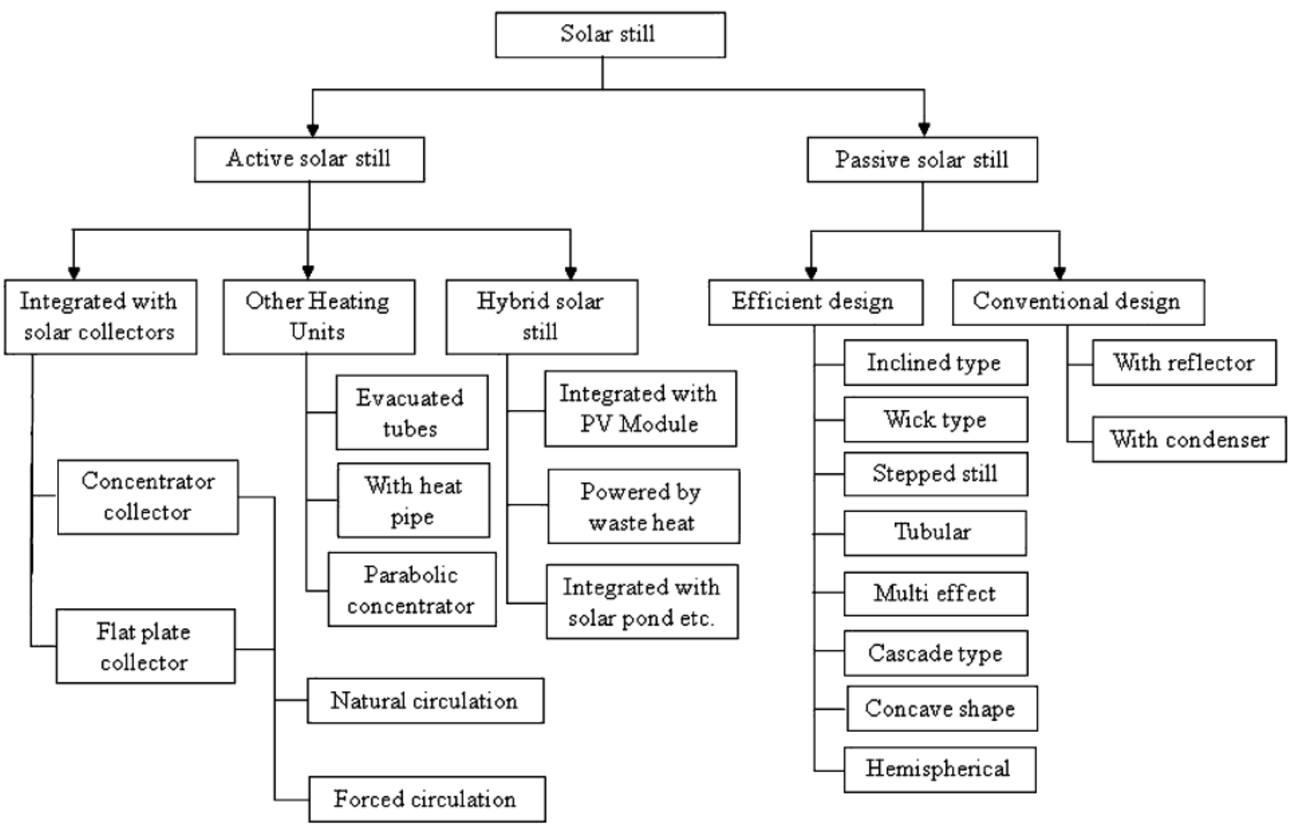
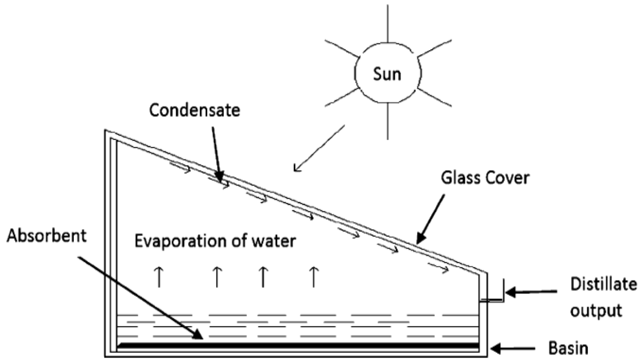



Figure 8-14: Different types of Solar Still from (Manchanda and Kumar 2015)



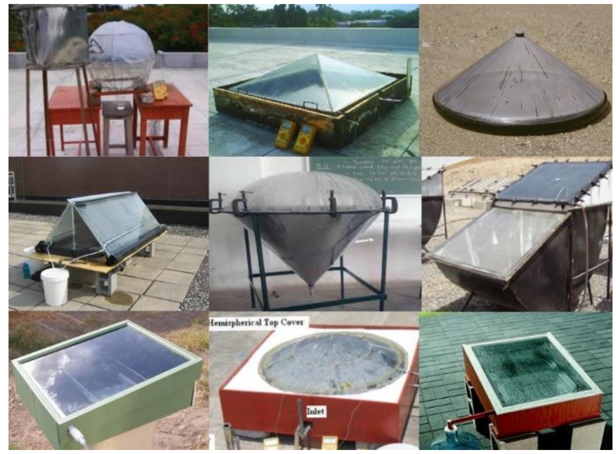



*Figure 8-15: Left: Simple Solar Still design with explanation of the desalination process (Manchanda and Kumar 2015). Right: Prototypes of different Solar Stills gathered by the researcher from different papers.*

### *Problem reframed and Biological Search consulting the GB-BID Database for Separation*

The GB-BID database on Separation was again utilized, this time with the following reframed problem: "how does nature extract moisture?". Organisms dealing with a separation strategy using evaporation/condensation process have been selected using keywords such as "extract"/"trap" in the "main action" and "sub-action" fields as well as "moisture"/water vapour" in the "Object" fields. The database produced the list below:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Environmental condition | Short description of mechanism | Active/ Passive |
|---|---|---|---|---|---|---|---|
| **Cacti** | **spines** | Extract | Moisture | air | Desert | Micro-textured spikes to coalesce water and move it via Laplace pressure | PA |
| **Orchids (epiphytic)** | **Roots** | Trap | Water/moisture | air | Various terrestrial | Water interception and Fast absorption by capillarity | PA |
| **TILLANDSIA Lanbekii** | **Leaves** | Extract | moisture | air | Desert | Water interception via narrow structures reducing boundary layer and with turbulences | PA |
| **Cotula fallax** | **Leaves** | Extract | Moisture | air | Desert | Condensation via Nano scale structure | PA |
| **Bromeliades (epiphytic)** | **Leaf** | Extract | Water/moisture | air | Forest environment | capillarity | PA |
| **Camel** | **Respiratory system** | Extract | Water/moisture | air | Desert | Condensation with optimized surface/volume ration | AC |
| **Namibian Desert beetle** | **Body surface (integument)** | Extract | Moisture | air | Desert Air moisture at sunset | Hydrophobicity/Hydrophillicity | PA |
| **Tick** | **mouth** | Extract | Moisture | air | Various | Hydrophillicity/Hygroscopicity | PA |
| **Thorny devil** | **Body surface** | Extract | Water/moisture | Soil/Air | Desert | Capillarity | PA |
| **Namib Desert Grass** | **Leaf** | Extract | Moisture | air | desert | Hydrophobicity assisted by micro-grooves | PA |
| **Nolana Mollis** | **Leaf** | Extract | Moisture | air | desert | hygroscopicity | PA |
| **Cribellate Spider** | **Silk web** | Extract | Water/moisture | air | Forest environment | Hydrophillicity | PA |

*Table 8-8: Result from filtering the GB-BID database in the fields "main action" and "object" using respectively keywords: extract/trap - moisture/water vapour. Also indicated a process attribute: Passive/Active.*

*Extracting Design Principles*

Interestingly almost all the organisms retrieved operate in similar context as the challenge (drylands). From the above organisms specific mechanisms/principles were extracted such as:

1. Increase of surface/volume ration to increase evaporation and condensation surfaces;
2. Micro/nano textured surfaces to manage surface tension and produce hydrophilic/phobic behaviour to coalesce moisture from air;
3. Capillarity to trap water and move it;
4. Hygroscopic materials to absorb moisture;

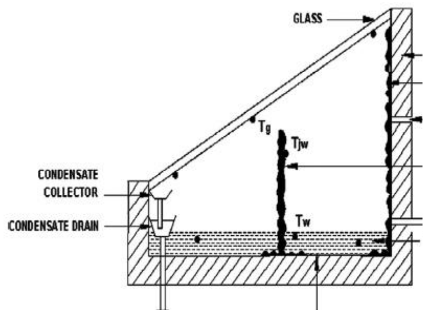
All the above mechanisms function passively without use of additional external source of energy.

*Applying the Design principles – the Mangrove Still and the Mangrove Technology Platform*

The principles extracted have been already singularly utilized in some of the existing designs of the solar stills. It is therefore relevant to see how consulting nature could lead to solutions which indeed had been already considered in human design by knowledge-based experts. The principles could give us however an indication on which strategies to apply, and, as a consequence, which ones already followed should possibly be abandoned. They could also be applied all together and not one at a time as often found in human design. Finally the principles could stimulate further research in biology to explore more detailed solutions for each one of them.

From the above principles, some initial technological solutions have been identified which allowed to start creating design concepts and prototyping:

| |
|---|
| **Design principle:** Increase of surface/volume ration to increase evaporation and condensation surfaces |
| In order to increase the evaporative surface exposed to sunlight it is proposed to create an overall transparent structure of the still with increased evaporating and condensing surface vis-a-vis the volume of the still. This is done using an undulated sheet made in transparent-sunlight resistant polycarbonate bent so as to create a tubular (or semi-tubular) structure. Inside the structure an undulated trough, made of the same undulated material would be inserted. Undulated surfaces are wider (around 15% more) than flat ones with the same projection (depending on the period of the sinusoidal shape), this means more surface exposed to the sun compared to volume and available for evaporation and condensation. Furthermore the undulation increase resistance to bending moment compared to flat one.<br>The design allows the use of a single undulated transparent sheet commercially available in DIY shops to easily build up almost the whole structure. The tubular/semi-tubular structure is almost fully transparent (apart the closures at the two sides of the structure) so sunlight can reach the evaporation surface for longer period of time than usual solar stills and orientation of the still toward the sun can be more flexible. |
| **Design principle:** Micro/nano textured surfaces to manage surface tension and produce hydrophilic/phobic behaviour to coalesce moisture from air |
| Different materials can be utilized which have different surface energy. Generally polymeric materials have hydrophobic properties which facilitate dropwise condensation. Because of the reduction of transparency of the condensing transparent surface due to drops formation, a rapid removal of drops is looked for.<br>Glass has hydrophilic properties which facilitate film condensation. Coating of condensing surfaces with hydrophilic/phobic material is feasible, however considered not financially viable comparing it with the performances of a solar still. |
| **Design principle:** Capillarity to trap water and move it |




The shape and transparency of the still should allow introducing wick materials and sponges in the trough in horizontal and vertical strips (we put cuts from black cotton T-shits to test) so as to move and distribute water by capillarity also in vertical planes and therefore increase evaporation surface.
The use and positioning of wick material should be designed in a way to increase evaporation surface avoiding re-condensation of vapour before it reaches the condensing surface.
Furthermore surfaces shall be oriented in order to optimize light interceptance.

*Figure 8-16: Schematic diagram of a single slope solar still with vertical jute cloth. (From: Sakthive M. "An experimental study on a regenerative solar stil lwith energy storage medium – jute cloth". Desalination – 2010)*

**Design principle:** Hygroscopic material to absorb moisture as well as to increase evaporation surfaces

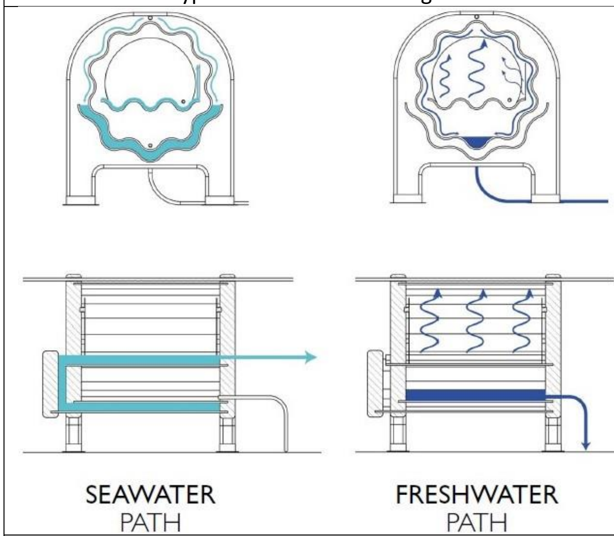
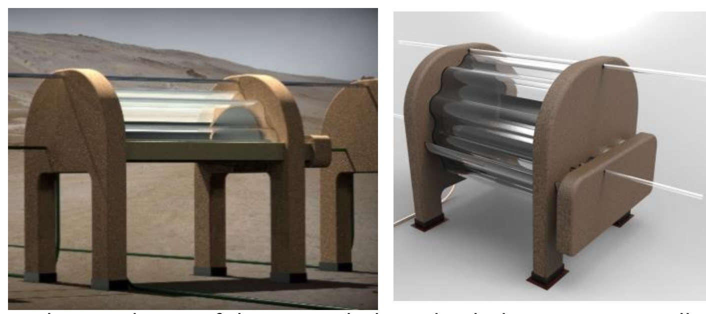
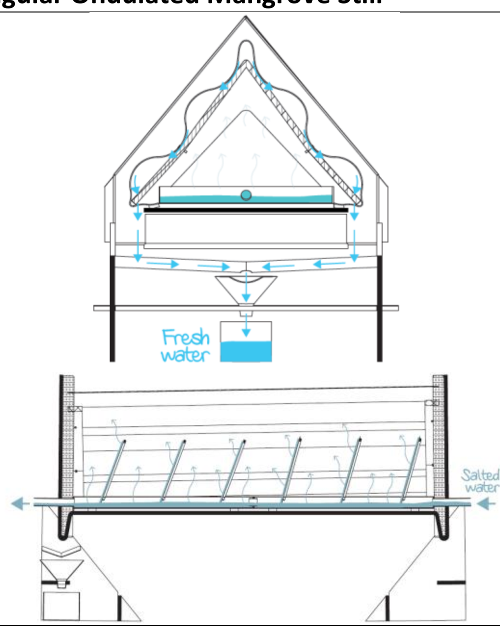
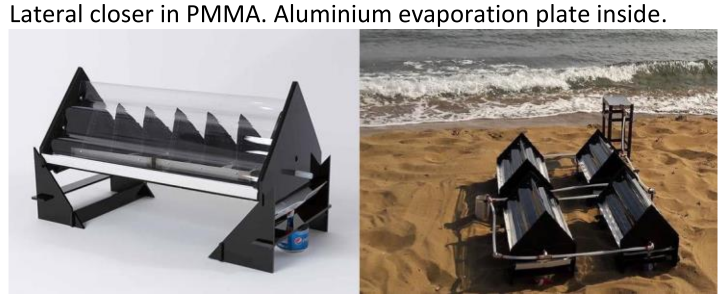
Hydrogels are physically or chemically cross-linked three-dimensional (3D) hydrophilic polymeric networks capable of absorbing large amounts of water (or biological fluids) and swelling. They have been used in several fields from medicine to agriculture and because of their hydrophilic properties and high water absorption they have also been proposed to be used for water desalination. Researchers investigated different paths that take advantage of the properties of hydrogels to use them for water desalination:
- Compression whereby the hydrogel operates as a sponge, which absorbs salt water and upon compression releases fresh water while trapping salt ions;
- Direct solar absorption to enhance water evaporation.
Hydrogel has excellent hydrophilicity and a large number of pores which can absorb water into its structure that consists of internal gaps, micron channels and molecular meshes, where the vaporization enthalpy of water is reduced. The structure is dyed with solar absorbers (polypyrrole) and solar energy is directly delivered to the small amount of water in the molecular meshes, leading to evaporation. As water evaporates, the pores are rapidly replenished by diffusion and capillary effect in the micron channels and internal gaps via swelling of the polymeric network to support a sustained high rate of vapour generation. The use and positioning of hygroscopic material should be designed in a way to increase evaporation surface avoiding re-condensation of vapour before it reaches the condensing surface.
*Despite its potential, hydrogel has not been considered so far into the prototypes proposed in this research.*

In order to make the solar still more efficient but also improve its applicability for land (re)generation, it needs to satisfy other technical/financial requirements which are usually not considered in current research such as:

- Maximize use of free energy (Sun, gravity). Processes should be passive as much as possible;
- Be Modular and Movable (so as to be adaptable to different contexts);
- Be light but sturdy;
- Easy to be assembled, dismantled and operated;
- Minimize use and waste of materials;
- Made with material easy to be found locally and recyclable;
- Allow recovery of salt;
- Affordable by low-income communities (very low Capex and Opex)

Following the above considerations the researcher, together with an engineering design student newly graduated reviewed the current passive solar still and how these are already embedded in the current design and eventually improve it. Following this analysis several designs and prototypes of improved solar stills have been carried out which have been named ***Mangrove Stills*** (in reference to the main biological analogy with the Mangrove ecosystems).

In the table below images and some details of the various Mangrove Still's prototypes which have been developed and tested throughout 2015 and 2018 (Table 8-9).

| | |
|---|---|
| **Tubular/Semitubular Ondulated Mangrove Stills** | |
| <br>Prototype of Semi tubular Mangrove Still | <br>Prototype of Tubular Mangrove Still |
| <br> | Evaporation/Condensation in a single chamber. Cover in Polycarbonate undulated sheet; Aluminium evaporation plate inside. Lateral covers in Polystirene.<br><br>Right: Rendering of the Semitubula and Tubular Mangrove Still.<br>Left: scheme of the path of fresh water produced and salt water. |
| **Triangular Ondulated Mangrove Still** | |
| <br> | Triangular structure. Evaporation/Condensation in a single chamber. Orientable black cotton wick material of triangular shape.<br>Cover in transparent Polycarbonate undulated sheet<br>Lateral closer in PMMA. Aluminium evaporation plate inside.<br><br>This prototype, submitted with the start-up Planet s.a.s (of which the researcher is co-founder) was selected among the six finalists of the Global Biomimicry Design Challenge of 2016.<br>Right: pictures of the prototype.<br>Left: scheme of the path of fresh water produced and salt water. |
| **Triangular/Eliptical/Circular section Mangrove Still** | |

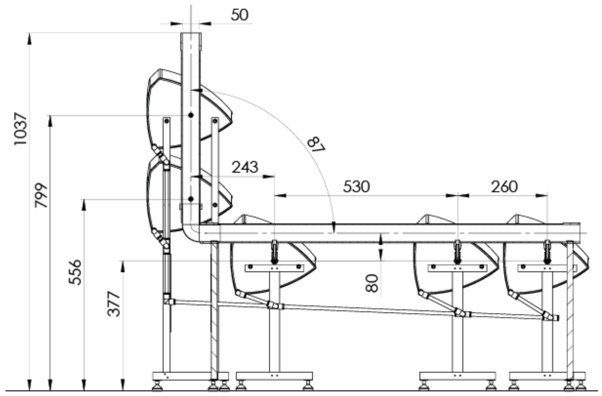
| | |
|---|---|
|  | Triangular/elliptical/Circular section structure:<br>Evaporation/Condensation in a single chamber;<br>PET foils as condensing transparent surface;<br>Plastic pot plates to close the structure on the sides;<br>Aluminium evaporation plates;<br>Cotton textile, Cellulose sponges as wick material.<br><br>Left: various prototypes. |
| **Mangrove Still System** | |
|  | <u>Internal structure:</u><br>• Aluminium plate (16 x 89 cm) painted black<br>• Cotton dark textile strip 8-10 cm high and 90 cm long as wick material attached and sustained by cellulose sponge bricks. Additional smaller textile strip at the sides of the plate.<br><u>External structure:</u><br>• Triangular section<br>• Cover material made in PET sheet (0,25 mm)<br>• Side closures made in transparent PMMA<br>• External cover tighten to the side closures via textile strip tighten with Velcro™<br>Left: scheme of the 10 units systems. |
| Closure of the lateral side using textile strips and Velcro<br> | Lateral closure, plate and wick material sustained by sponges<br> |

*Table 8-9: Examples of design and prototypes of the Mangrove Still developed through 2016-2018.*

All the prototypes have been tested for water production in Cyprus, for several days, during summer months showing a production of around 2-2,5 L/day/m$^2$. Therefore the researcher believes that further optimizations in the design and precision in assembling it, it could lead to a production of at least 3-3,5 l/day/m$^2$ in appropriate locations and weather conditions. These are productions compatible with other passive solar stills, however when considering the cost for materials to build the still (around 35$ per m$^2$ of evaporation surface), the Mangrove Still has the potentiality for becoming competitive with other solar stills existing in the market. The current cost and water production of the still was compared with other similar designs developed in academic environment (see Figure 8-17). Furthermore a business plan was carried out (Planet s.a.s 2016) which determines a viable sale price of the still and compared it with similar products already on the market (Table 8-10) confirming the competitiveness of the Mangrove Still.

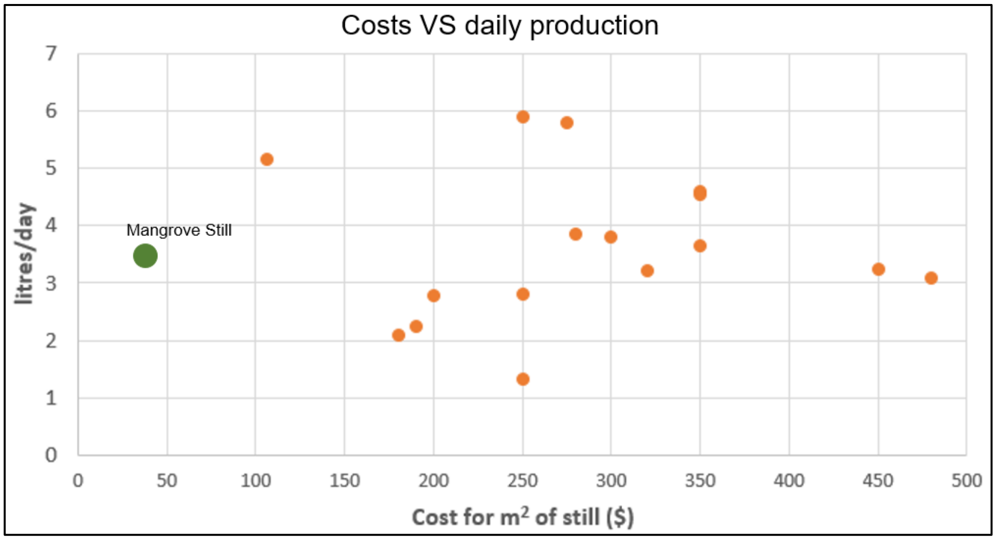



*Figure 8-17: Cost analysis of different solar still configurations tested in Academic environment from (Kabeel, Hamed, and El-Agouz 2010) including the Mangrove Still.*

| | Mangrove Still | Aquamate (floating) | Rainmaker (SolAqua) | Cleardome |
|---|---|---|---|---|
| **Price ($) x m$^2$** (n. of stills to reach 1 m$^2$) | 300 (2) | 480 (2) | 525 (1) | 1000 (2) |
| **Output (x m$^2$)** | 2,2-3,5 l / day | 1-3 l / day | 2- 5 l / day | 2- 5 l / day |
| **Price x Lt/d ($)** – av. prod. | 107 | 240 | 150 | 285 |
| **MS Price x Lt vs benchmark** | 0 | -56% | -30% | -63% |
| **Cost x Lt ($)** | 0,05 | 0,16 | 0,11 | 0,21 |
| **Payback period** (based on 1lt bottle at 0,2$) | 17 months | 52 months | 34 months | 68 months |
| **Target Customers** | Land/Domestic Usage | Survival in opewater | Domestic Usage | Domestic Usage |

*Table 8-10: Comparison of different factors between the Mangrove Still and other Solar Stills on the market*

### *The Mangrove Technology Platform - From single technology to system of technologies*

In order to expand the biological analogy with a natural ecosystem such as the one of the Mangroves and to create a coherent and integrated system for soil regeneration and food production, the Mangrove Still desalination system was combined with other two innovative technologies: **organic incubators** to foster crop resilience; and a robust **IoT system** to drive production parameters. This project has been carried out

with the company *Planet s.a.s* in cooperation with other two companies: *Plantasia* and *Ultrafab* which developed respectively the organic incubator and the IoT system.
The overall system, scalable and adaptable, has been named **Mangrove Technology Platform**. The idea was considered innovative enough to receive a grant in 2017 from the Expo 2020 Dubai – Expo Live Programme which selects and provide grants to innovators world-wide with the aim to show case them at Expo 2020 (the project was among other 120 on 11000 which received the grant). The grant allowed to improve the design and pilot test the concept.
In order to start testing and initial pilot combining these three technologies, a system was set up in Akrotiri, Cyprus, in March 2018 which includes:

**1. Mangrove Still system**: 10 units assembled into a system with 6 horizontal unit and 4 vertical (Figure 8-18).
Salty water path: The current system works in batch. The saline water is pre-heated in a black pipe before feeding the central pipe which distributes the water into the units. The level of water in the unit is around 2-3 mm. Salty water is also absorbed by capillarity by the sponges and textile increasing the surface of evaporation of 50%. The overflow (brine) gets collected into external aluminium plates where it slowly evaporates producing salt crystals. The system is fed once a day allowing for purging the units from brine.

Distilled water path: The water, condensed on the internal surface of the transparent cover, drips along the surface reaching the lower apex of the triangular structure. The upper apex is positioned in a way to be out of the plate. This allows the drops of condensate in the upper apex not to fall back in the plate. The condensate is then collected at one side of the unit (thanks to a certain minimal slope) and drained away by piping system where all the water produced by the units gets collected. Finally a distilled water tank collect all the water produced by the system. The water is utilized for irrigating the organic incubators. The base of the system was also enclosed in a plastic foil so as to gather rainfalls and have it mixed together with the distilled water so as to increase the overall water production (Figure 8-20).

*Figure 8-18: (left) Mangrove Still (MS) system in Akrotiri; (right) LifePatch with plants irrigated by water produced by MS system.*

**2. Organic Incubator - LifePatch** –developed by the Chilean start-up *Plantasia (www.lifepatch.cl)*. The organic incubator is a vegetal mat which facilitates the revegetation of soil in areas with low fertility conditions. Thanks to its structure of organic fibres it can act as a nutritional matrix for plants and also be inoculated with additional nutrients or fungi which assist the development of plants roots and withhold water. The current size of the fibre mat is 50x50cm. 2 mats have been set with local seedlings and irrigated via drip irrigation with the water produced by the desalination system (Figure 8-18).

**3. Internet of Thing (IoT) system -** The system, designed by Ultrafab (www.ultrafab.it), is a modular, scalable all-weather mesh network incorporating wireless sensors, real-time alerts and an analytics dashboard (Figure 8-19). The heart of the system is the application server operating web-based software that collects and processes data from the nodes (sensors), verifies the applicable algorithms, manages users, archives information and activates the nodes. Nodes are hardware relays connected to devices such as pumps, valves, switches, energy generators and communication routers for the interaction between the server, the integrated units and the environment. The nodes constitute a network transmitting information to a central unit that rebroadcast the signal to a cloud-based server. A wide range of node combinations are possible and so far, a set of five dedicated sensors have been developed and installed: for temperature, relative humidity, wind intensity and water quantity.

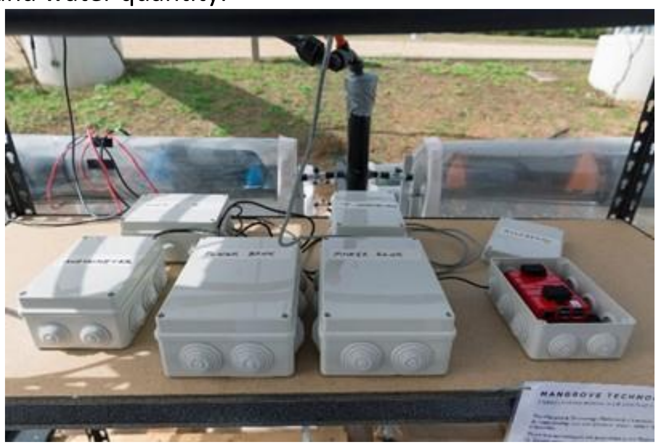


*Figure 8-19: Data collectors of the IoT system with connection to sensors of Temperature and Humidity.*

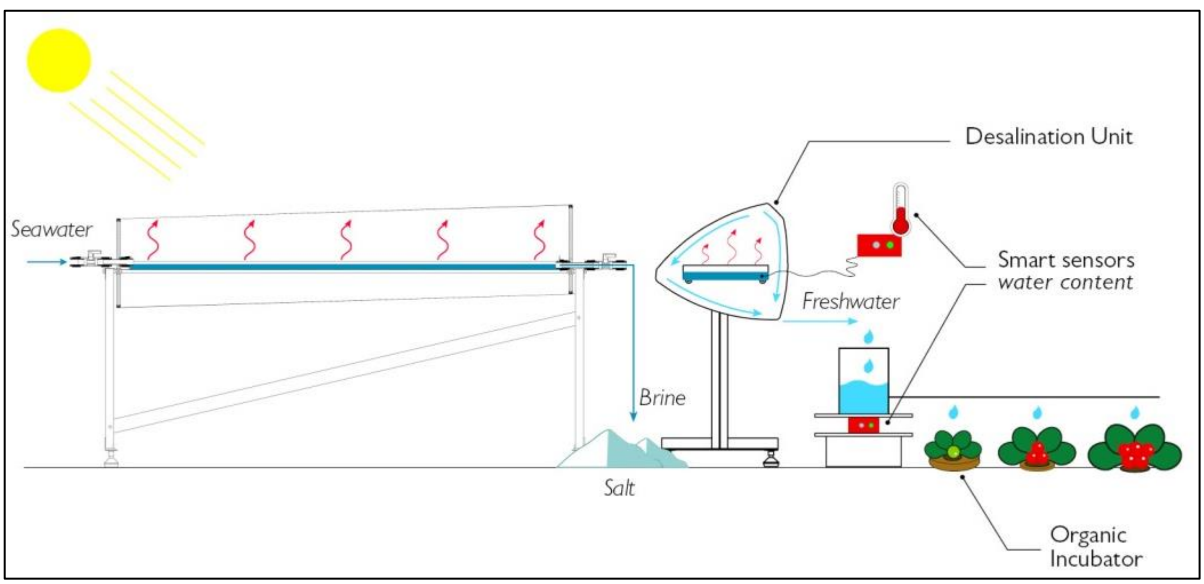



*Figure 8-20: Scheme of the Mangrove Technology Platform integrated system.*

The system assembled was tested between end of March 2018 and mid July 2018. This allowed assessing the functioning and performance of the system in different seasons and different weather conditions allowing better understanding of its behavior and identifying shortcomings in the design to be improved.
In particular it was measured a production per unit of around 0.5-0,6 L/day which would lead to a production of around 5 L/day/m2 of evaporating surface. This however should take into consideration that

the feed water was coming from the salt marsh and had a salt concentration double the seawater (around 7g/L), that salt indeed started to rapidly crystalize inside the plate especially the plate was left getting dry. This prevented removing the crystalized salt unless the unit was open and clean manually. The thin transparent cover of the unit became also an issue after around three months of testing as the effect of the sunlight combined with strong gusts of winds (Akrotiri is indeed subject to frequent strong winds) causes some cracks in the cover of some units with consequent loss of vapour.

*Conclusions of the case study*

The case study of the Mangrove Still and Mangrove Technology Platform aimed at showing the potentiality of the GB-BID database for separation to generate innovative ideas. The results achieved in this case study are promising.

The design concept developed, as highlighted in Table 8-10: Comparison of different factors between the Mangrove Still and other Solar Stills on the market and Figure 8-17, it is competitive with other existing similar products, some of which already on the market (comparable water production but at least 50% lower production cost). One relevant element of the process it has been the abstraction of the biological solution from the organism level (the Mangrove Tree) to the ecosystem level (the Mangrove Ecosystem). Understanding the organism and its strategy within the broader context of the ecosystem within which it thrives, allowed to extract a principle not linked to a possible improvement of the technology but to a change in its functionality (applicability): from producing water for human consumption, to producing water for the land. This opened up to new market opportunities for this technology (the solar still) previously not explored. In particular, within this application, the technology does not only have a market on its own (low-cost desalination for land regeneration), but it can also expand the market of other products and services enabling them to operate in contexts (abundance of saline water) previously un-accessible.

Moving from ideas to prototyping and then to product development has challenges. Nevertheless, the researcher believes that the progress achieved so far by the company Planet s.a.s. with this design concepts can be accounted as indicator of usefulness of the GB-BID method.

The progresses achieved were convincing enough that the Mangrove Technology Platform was included as innovative demonstrator for circular economy in the EU Horizon 2020 project *Hydrousa* (27 European partners and six demonstrator technologies to be tested). A revised design of the technology is currently on-going and an up-scaled system to produce 200L/day of water from seawater and desalination plant's brine will be set up on the island of Tinos (Greece) in June 2020. The water produced will be utilized to cultivate fruits and vegetable in greenhouse.

### 8.4.2 Bio-Cover – Anti-Bacterial surface

**Problem:** *how to reduce the settlement of bacterial colony (bio-films) on surfaces*

Below, the process of problem-driven approach that has been followed which considers the consultation of the GB-BID database on separation to carry out the biological search:

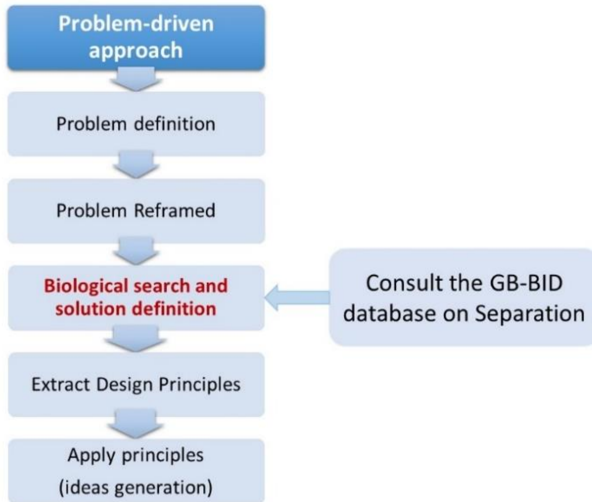



*Figure 8-21: Problem-driven approach followed which led to Bio-cover ideation.*

### *Problem Definition*

### *Short background about the context: Nosocomial and foodborne illnesses*

In Europe, 5-12% of hospitalized patients develop *healthcare associated infections* (or *nosocomial infections*) due to bacteria; 25,000 deaths per year are estimated to be attributable to these infections. The most frequent infections are those related to surgical wounds, urinary tract infections, lower respiratory tract infections and bloodstream infections. It is estimated that nosocomial infections causes extra EU in-hospital costs of approximately € 1 billion/year and productivity losses of approximately € 600 million/ year. In the US, according to the Centers for Disease Control (CDC), nosocomial infections affect about 2 million patients annually and result in almost 100,000 deaths per year. Costs for curing and prevention range from $4.5 to $11 billion a year (Stone 2009).
The control of bacterial growth in order to reduce nosocomial infections is generally tackled by activating preventing measures such as hygiene practices and utilizing "kill" technologies including antibiotics, disinfectants and dangerous chemicals (containing silver ions that can poison and cause hazard to the environment). However, kill strategies and their overuse have led to subsequent increased bacterial resistance, further causing harm to people and the environment. There is therefore the need for a cheaper but effective way to protect people from nosocomial infections without causing harm to the environment and without risking to create new generations of resistant bacteria (Stone 2009).

*Foodborne illnesses* usually arise from improper handling, preparation, or food storage. Good hygiene practices before, during, and after food preparation can reduce the chances of contracting an illness. There is a consensus in the public health community that regular hand-washing is one of the most effective defenses against the spread of foodborne illnesses. In industrialized countries, the percentage of the population suffering from foodborne diseases each year has been reported to be up to 30%. In the USA, for example, around 76 million cases of foodborne diseases, resulting in 325,000 hospitalizations and 5,000 deaths, are estimated to occur each year. (from WHO https://www.who.int/news-room/fact-sheets/detail/food-safety) There is therefore the need to increase food safety preventing foodborne illnesses due to improper handling, preparation, or food storage.

In both nosocomial infections and foodborne illness the colonization of bacteria on surfaces, which can be touched by hands with the following transmission of a disease, plays a crucial role. How do bacteria colonize a surface?

### *The process of bacterial adhesion to surfaces*

Since adhesion is the first step of biofilm formation, understanding bacteria-surface interactions is essential for biofilm control. Bacterial cells approach surfaces by different means, including Brownian motion, sedimentation, movement with liquid flow, bacterial motility with cell surface appendages, and interaction with other cells to form aggregates. None of the theoretical models developed to date can however accurately describe the adhesion of all bacteria on different surfaces. (Song, Koo, and Ren 2015).

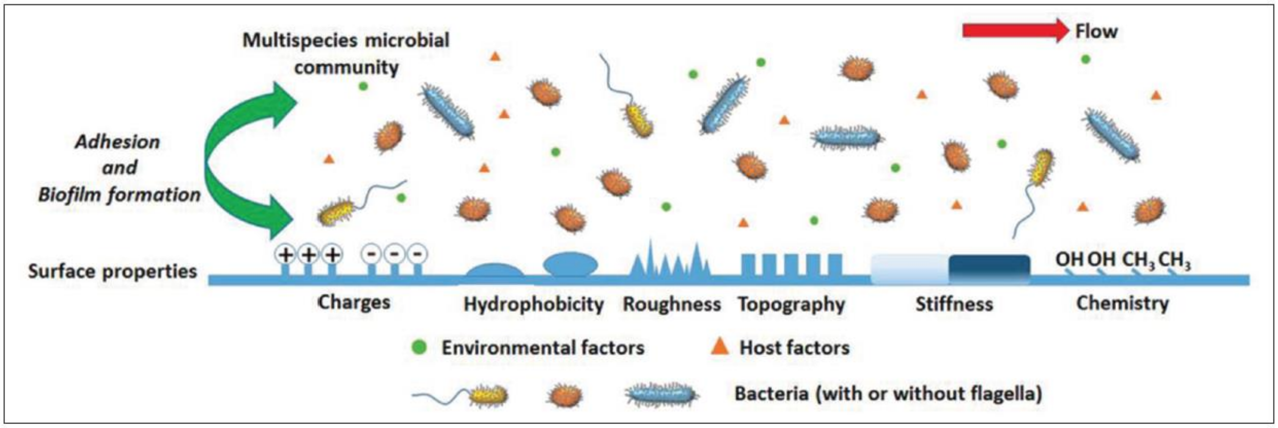



*Figure 8-22: Schematic illustration of bacterial adhesion and the effects of material properties in complex environments. The effects of surface charge, hydrophobicity, roughness, topography, and stiffness are discussed in this review. (Song, Koo, and Ren 2015)*

The following factors play a role in bacteria adhesion: *surface charge, hydrophobicity, roughness, topography, and stiffness and chemistry*.

Surface charge plays an important role in determining the binding force between bacteria and the surface, and it has long been known to affect biofilm formation. Most bacterial cells are negatively charged; thus, in general, a positively charged surface is more prone to bacterial adhesion, and a negatively charged surface is more resistant to bacterial adhesion. In general, by tuning the hydrophobicity of a surface, bacterial adhesion can be either promoted or inhibited.

In addition, recent research showed that super-hydrophobic and super-hydrophilic surfaces can both prevent biofilm formation. Besides super-hydrophobic surfaces, super-hydrophilic surfaces have good non-fouling properties due to the formation of a dense layer of water molecules, which weakens the interaction between cell surface and substratum material and thus reduces cell adhesion (Song, Koo, and Ren 2015).

In general, an increase in surface roughness promotes bacterial attachment due to the increase in contact area between the material surface and bacterial cells and protection from shear forces. Thus, smoothening the surface can reduce biofilm formation. However, the exact effects of surface roughness on bacterial adhesion and biofilm formation vary with the size and shape of bacterial cells and other environmental factors (Ramakrishna et al. 2011). Thus, there is no universally optimum roughness that can repress adhesion of all bacterial species.

Increasing data have shown 1) that the conventional definition of roughness, based on the average amplitude of peaks and valleys, is not sufficient to describe the 3-dimensional features of a surface and 2) that the distribution of peaks and valleys is also important to microbial biofilm formation. Recent advancements in material and surface engineering have brought exciting opportunities to create surfaces with not only controlled overall roughness but also well-defined topographic patterns to control biofilm formation (Hasan, Crawford, and Ivanova 2013). In addition to the well-known example of Sharklet

surfaces (described in next section), many micrometre and nanometre-scale topographic patterns with varying shape and size have been shown to inhibit biofilm formation compared to flat surfaces of the same material; such as protruding and receding squares, circles, and parallel channels on polydimethylsiloxane; cone-shaped patterns of silicone and ridges on PDMS (Laha et al. 2013).
When the distance between the features is significantly smaller than the bacterial dimension, it creates an obstacle at the bacterial diffusion and motility (caused by friction between membrane cell and the wall of the features) to such an extent that to pass through this kind of channels bacteria can also leverage on reproduction, decreasing their speed and causing different level of deformations (Laha et al. 2013).
The stiffness is directly connected with a phenomenon known as mechano-trasduction, describing the mechanical forces exerted on and sensed by the microorganisms (Paluch et al. 2015). The geometric dimensions including width, length, and height of the topographical feature as well as the modulus of the base material define its stiffness. Consequently, (excluding changes in material) geometrically different topographical features have a different stiffness.
When a bacterium adhere to such a surface, it generates a bending moment on the features causing a nano-force gradient which induces a stress gradient on the membrane and destabilizing and disrupting normal cell functions (Hasan, Crawford, and Ivanova 2013).

Following the above background, the problem has been identified: *how to reduce the settlement of bacterial colony (bio-films) on surfaces.*

### *Problem reframed and Biological Search consulting the GB-BID Database for Separation*

The above mentioned problem was therefore re-framed or “biologized” in order to undertake a biological search. Questions such as “How does nature avoid bacterial colonization?” or “How does nature stay clean?” or again “How does Nature repel/exclude external entities?” have been considered. Using these keywords to consult the GB-BID database filtering the fields “main action” and “object” it produced the following list of organisms (Table 8-11). To be highlighted that because only one entry of the database was about “repelling bacteria”, the query has been extended also to action’s objects such as “water” (in “air” as process condition), which plays a role as substrata for bacteria proliferation, as well as “oil” and “ions”:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Separation Principle | Active/ Passive |
|---|---|---|---|---|---|---|
| **Birds** | **Feathers** | Exclude | Water | Air/Water | Surface tension regulation | PA |
| **Lotus** | **Leaf** | Repel | Water/particles | Air | Surface tension regulation | PA |
| **Shark** | **Skin** | Repel | bacteria/organisms | Water | Adhesion and Surface tension regulation via micro morphology and vortexes | PA |
| **Rosa montana** | **Petals** | Repel / attract | water | Air | Surface tension regulation via micro morphology | PA |
| **Viola tricolor** | **Petals** | Repel | water | Air | Surface tension regulation via micro morphology | PA |
| **Cicada A. bindusara** | **wings** | Repel | water | Air | Surface tension regulation via micro morphology | PA |
| **Cicada M. opalifer** | **wings** | Repel | water | Air | Surface tension regulation via micro morphology | PA |
| **Cicada C. atrata** | **wings** | Repel | water | Air | Surface tension regulation via micro morphology | PA |
| **Leafhoppers (cicadellidae)** | **wings** | Repel | mainly water (little repel oil | Air | Surface tension regulation via micro morphology | PA |

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Separation Principle | Active/ Passive |
|---|---|---|---|---|---|---|
| **Collembola (springtail)** | **Body** | Repel | water & Oil | Air | Surface tension regulation via micro morphology | PA |
| **Colocasia esculenta (Taro)** | **Leaf** | Repel | Water | air | Surface tension regulation via micro morphology | PA |

*Table 8-11: Result from filtering the GB-BID database in the fields "main action" and "object" using respectively keywords: repel/trap/exclude – water/oil/bacteria. Also indicated the medium, the separation principle and a process attribute: Passive/Active.*

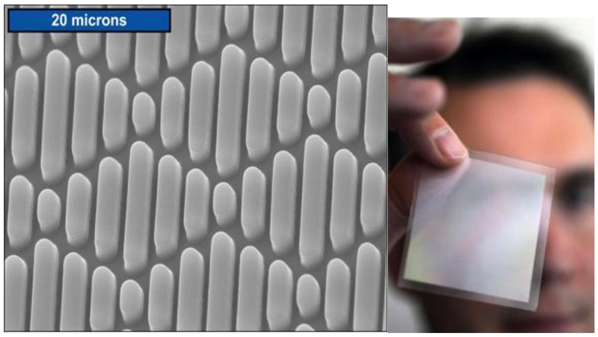
A search in AskNature was also carried out looking at functions such as "protected from dirt/solids", which provided biological solutions similar to the one extracted from the GB-BID database, and "protect from microbes" and "protect from fungi", which provided two biological solutions (the seeds of the lotus plant and the seeds of the Polynesian box fruit), whose descriptions do not reveal any connection with defence from microbes.

All the organisms retrieved actuate a passive mechanism:

- Micro/nano texture of surface to manage surface tension;
- Micro/nano texture of surface to manage adhesion.

The only reference around anti-bacterial property concerns the skin of the sharks. Shark's skin is covered by very small individual tooth-like scales called *dermal denticles*, ribbed with longitudinal grooves (aligned parallel to the local flow direction of the water). These grooved scales reduce vortices formation present on a smooth surface, resulting in (pressure and friction) drag reduction. The dermal denticles are aligned along the body axis and have a diamond-like shape. They are generally formed by V-shaped riblets with height that varies between 200 and 500 µm, and their space varies between 100 and 300 µm. The riblets work by impeding the cross-stream translation of the streamwise vortices in the viscous sublayer. The mechanism by which the riblets interact with and impede vortex translation is complex, and the entirety of the phenomena is not yet fully understood. On a practical level, impeding the translation of vortices reduces the occurrence of vortex ejection into the outer boundary layers as well as the momentum transfer caused by tangling and twisting of vortices in the outer boundary layers.

The micro-texture of the dermal denticles also shows super-oleophobic properties in water. Anti-fouling/self-cleaning properties have been speculated but not properly tested. The roughness of the denticles seem to create an unfavourable energetic condition for bacteria to attach. Tests have been conducted by the company Sharklet in their endeavour of designing an anti-bacterial surface. According to these tests, the engineered surface, called indeed Sharklet, delays the colonization of biofilms up to 14 days compared to a non-textured surface (Figure 8-24).
The engineered and patented surface is made up of millions of tiny raised, microscopic features impressed on several types of polymers layers arranged in diamond shapes to form a pattern and embedded in different plastic materials.




Each diamond measures 25 microns across (about 1/5th the thickness of a human hair) and contains seven raised ribs of varying length. Laboratory tests suggest that the Sharklet™ pattern disrupts several important microbial colonizing processes that are necessary for bacteria to develop into a biofilm. In strenuous laboratory tests, the product has proven effective at controlling bacteria such as *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *E. coli* among others.

*Figure 8-23 Sharklet™ pattern. From Sharklet.com*

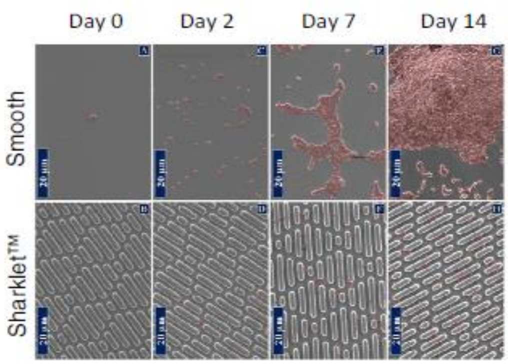



*Figure 8-24 Sharklet™ pattern and bacterial analysis for s. aureus. From Sharklet.com*

- Day 0—Bacterial presence at 1 percent on smooth surface versus 0 percent on Sharklet
- Day 2—Bacterial presence at 7 percent on smooth versus 4 percent on Sharklet. No biofilm on either surface.
- Day 7— Bacterial presence at 22 percent on smooth versus 4 percent on Sharklet. A biofilm has formed on the smooth surface.
- Day 14– Bacterial presence on smooth versus 7 percent on Sharklet. No biofilm on the Sharklet™ surface.

In order to design and test a different design, not only the geometrical texture on shark's skin was considered, but also other patterns present on organisms such as plant's leaves, flowers, wings, etc. Micro-nano textures in nature are most often represented by pillar structures (cylindrical, conical, with undulated sections, etc.) with different densities (Gorb 2009). If these patterns allow the management of properties such as wettability, drag, adhesion, friction, heat dissipation, their production and especially replication for industrial application is still a challenge due to their size as well as their durability. In nature these patterns are subject to operating conditions of several order of magnitude lower than the one they could be subject in industrial environment.

From here the effort in trying to design an anti-bacterial pattern which could also promise a certain durability when subject to human operating conditions. For this purpose, riblets rather than pillar should be preferred as they possess better stiffness. Among the surface patterns listed inside the GB-BID database, the texture of epithelial cells of Teleostean fish gills have been reported as providing extra resistance to stresses (a listed extra-action in the database) (Figure 8-25). However no research has been found reporting about their possible anti-bacterial function.

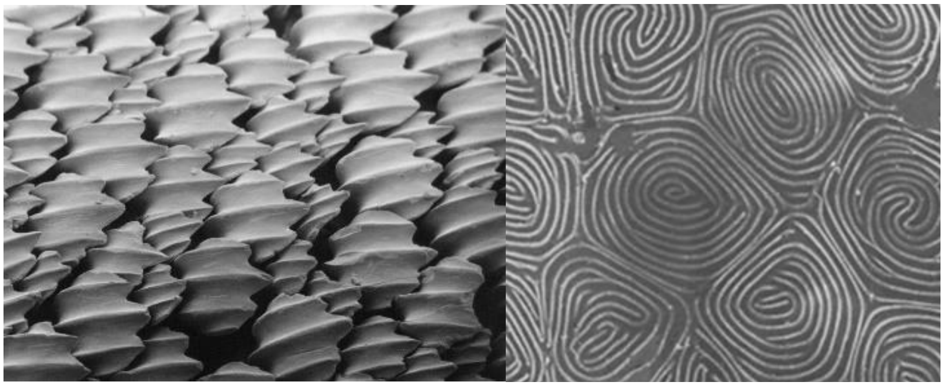


*Figure 8-25: Left: dermal denticles on skark's skin; Right: ephitelian cell of teleostean fish's gill. From (De Pasquale 2018)*

### *Extracting Design Principles*

From the Shark's skin and the epithelial cells of teleostean fish specific mechanisms/principles were extracted such as:

1. V-shaped riblets with height that varies between 200 and 500 μm, and their space varies between 100 and 300 μm.
2. Micro ridges with spiralling patterns on a surface to avoid bacterial colonization

### *Applying the Design principles*

Therefore a combination of the shark's dermal denticles and the texture on the surface of the epithelia cell of the fish were utilized as inspiration to design a micro texture to be tested for its anti-bacterial properties. The geometry below was designed and named **Bio-Cover** (Figure 8-26**)**:

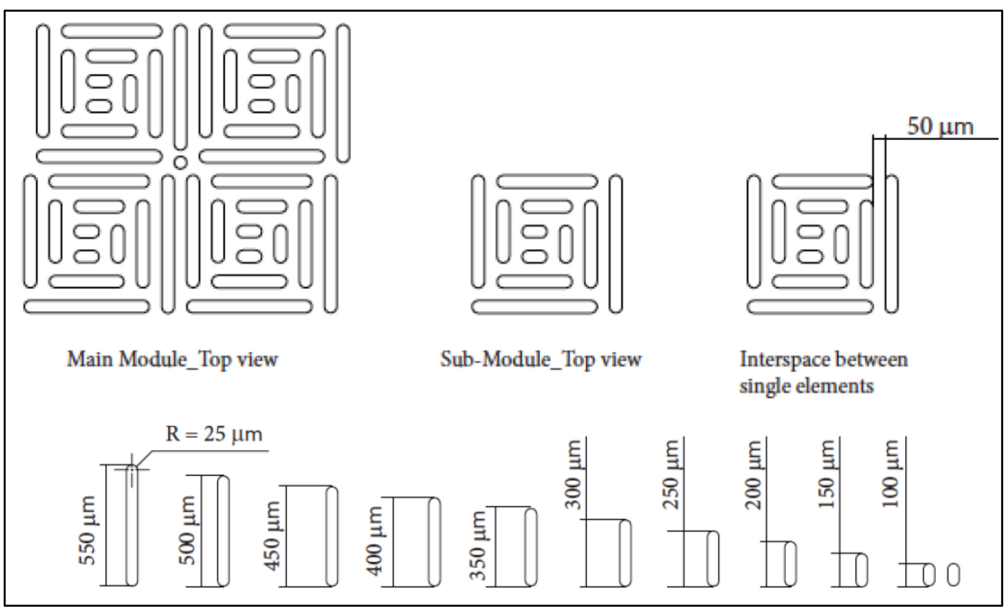



*Figure 8-26: Design of the pattern Bio-cover.*

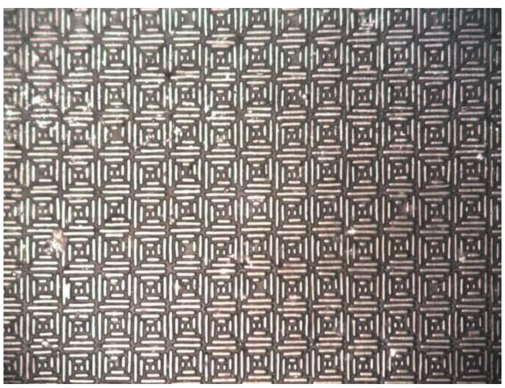
The length of the segments composing the spiral geometry has been determined to be in line with the order of magnitude of the riblets of the dermal denticles of the sharks, their distances (50 μm) to be proportionate to the distance between the spiralling riblets of the epithelian cells. The height of the riblets is 20μm.

The textured surface is an isotropic repetition of the single element where at the intersection among four elements a pillar has been inserted in order to reduce the gap and hypothetically avoid bacteria to settle in that space.

*Prototyping and testing the engineered surface*

In order to prototype the surface and produce samples to be tested, the company Hoowaki was identified which is specialized in surface micro texturing utilizing advanced tools such as photolithography, laser ablation, e-beam lithography, nano-imprint lithography and any combination of these. The anti-bacterial tests have been designed together with and carried out by the Food Lab (a certified Lab applying ISO17025 in Cyprus). To conduct the tests the following sets of micro-textured plaques have been produced (in 05/2017):

- 12 5x5cm polypropylene (Braskem RCP RP 250 polypropylene) plaque samples with the anti-microbial pattern (Figure 8-27);
- 12 5x5cm polypropylene plaques with as smooth control samples molded from a polished silicon wafer. The back of the smooth control is not polished and appears rough compared to the polished side.



*Plaque at 500x*

Plaque 5x5cm

*Figure 8-27: Bio-cover plaque (right); image at 500x showing the pattern (left)*

To be noticed how, at 500x, the pattern of single spiralling elements spread on a surface resembles two sets of Sharklet patterns crossing perpendicularly. This was not done on purpose and not noticed at the moment of the design. It could be just a coincidence or an indication that indeed the use of sets of parallel riblets with different orientation is an effective pattern utilized by nature to deal with adhesion regulation. The anti-bacterial test was conducted by FoodLab in Cyprus (during 06/2017-03/2018) for 60 days with the following bacteria: TVC, Coliform, E Coli, St. Aureus, Salmonella, Listeria, Enterococcus and Pseudosomonas Aeruginosa.

The calculation of bacteria on the plaques with the pattern, on the ones without (control) and in the blank sample (water with no plaques) has been done three times in three different time intervals (on the same material samples). The plaques were submerged in still water within petri dishes.

*Table 8-12: results of the anti-bacteriological experiment on Bio-cover. (Foodlab)*

| Laboratory results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Day** | **Material** | **TVC (22C)** | **Coliform** | **E.coli** | **St. aureus** | **salmonella** | **listeria** | **enterococcus** | **Pseud. aeruginosa** |
| | | /ml | /100ml | /100ml | /100ml | /100ml | /100ml | /100 ml | /100ml |
| Day 0 | **Control** | $1.0X10^{4}$ | $2.4X10^{1}$ | $2.0X10^{1}$ | $3.0X10^{2}$ | $1.0X10^{2}$ | $1.0X10^{2}$ | $2.5X10^{1}$ | $1.1X10^{2}$ |
| | **BI** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **patten** | $1.0X10^{4}$ | $2.4X10^{1}$ | $2.0X10^{1}$ | $3.0X10^{2}$ | $1.0X10^{2}$ | $1.0X10^{2}$ | $2.5X10^{1}$ | $1.1X10^{2}$ |
| | | | | | | | | | |
| Analysis after 7 days | **Control** | $12.0X10^{4}$ | $22.3X10^{1}$ | $23.0X10^{1}$ | $43.0X10^{2}$ | $21.0X10^{2}$ | $42.0X10^{2}$ | $13.7X10^{1}$ | $201.1X10^{2}$ |
| | **BI** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **patten** | $4.0X10^{4}$ | $4.6X10^{1}$ | $4.0X10^{1}$ | $5.0X10^{2}$ | $1.5X10^{2}$ | $1.9X10^{2}$ | $3.5X10^{1}$ | $10.1X10^{2}$ |
| | | | | | | | | | |
| Analysis after 15 days | **Control** | $3.0X10^{6}$ | $9.1X10^{4}$ | $9.0X10^{4}$ | $1.9X10^{4}$ | $4.0X10^{5}$ | $4.0X10^{3}$ | $1.3X10^{4}$ | $2.4X10^{6}$ |
| | **BI** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **patten** | $12.0X10^{4}$ | $15.3X10^{1}$ | $14.2X10^{1}$ | $22.0X10^{2}$ | $21.4X10^{2}$ | $31.7X10^{2}$ | $42.6X10^{1}$ | $120.1X10^{2}$ |
| | | | | | | | | | |
| Analysis after 30 days | **Control** | $>3.0X10^{9}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ |
| | **BI** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **patten** | $4.3X10^{6}$ | $4.5X10^{3}$ | $5.7X10^{3}$ | $6.2X10^{4}$ | $1.5X10^{4}$ | $2.3X10^{4}$ | $6.0X10^{3}$ | $2.3X10^{5}$ |
| | | | | | | | | | |
| Analysis after 60 days | **Control** | $>3.0X10^{9}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ |
| | **BI** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **patten** | $>3.0X10^{9}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ | $>1.5X10^{8}$ |

The experiment showed (Table 8-12) a delay in the multiplication of bacteria on bio-cover until at least 15 days (the order of magnitude of number of bacteria on bio-cover is stable compared to the bacteria on the control plaque). Following the 15 days, as replication of bacteria accelerates also on bio-cover when on the control plaque already reached its maximum, it is no possible to claim further anti-bacterial property.

### *Conclusions of the case study*

Even if results are not conclusive and further experiments should be undertaken, they are nevertheless promising. The Bio-Cover pattern, whose design has been inspired by biological solutions present in the GB-BID database, shows anti-bacterial performances at least comparable to the Sharklet's pattern in terms of delaying the colonization of surface by several type of bacteria. This delay would reduce the frequency of cleaning of surfaces with consequent reduction of its cost and use of potentially environmentally un-friendly cleaning substances.

Because of the challenges of reproducing bio-inspired surfaces on large surfaces and their limited (in fact not extensively tested) durability in many of the operating conditions, Sharklet Technology positioned itself in the market for bio-medical devices. In particular, it develops applications of the Sharklet pattern on small polymeric surfaces (in the order of $mm^2/cm^2$) such as catheters and blood dialysis equipment. In so doing, the operating conditions and the size of the surfaces are similar to the one found in nature (ex: blood circulation in arteries) and in addition, the market segment selected guarantee a high benefit/cost ration.

The scope of Bio-cover was to address the weaknesses of Sharklet designing a pattern which could resist in operating conditions more challenging than the one found in nature. From this the reason of combining the pattern of the dermal denticles of shark with a more stiff profile of the teleostean fish epithelial cells and to have the pattern impressed on rigid plastic.

The anti-bacterial test has been carried out within the activity of an EU funded project lead by Whirlpool – Italia (project called *Hot and Cold*) to identify pattern suitable to be reproduced with commonly available

production processes (in this case with injection molding) on house appliances such as fridges and ovens. Tests regarding the industrial reproducibility and durability are currently on-going.
In parallel to these tests, it has been recently identified that also the superficial pattern of the leaf of the Taro seems possessing anti-bacterial property in water (the Taro leaf is also included in the GB-BID-database with main function "repel water in air" and only recently it was added "repel bacteria in water" as sub-function) (Hasan, Crawford, and Ivanova 2013). Therefore, studies are on-going exploring this geometry to assess its potential also compared to bio-cover.

## 8.5 Across-sector Case Studies

### 8.5.1 Anti-flashover High Voltage Insulators

**Problem:** *how to reduce risk of flashover on High Voltage Insulators*

The GB-BID database on separation has also been tested to generate ideas to solve problems not related to the separation technology sector.

Planets s.a.s was commissioned to investigate the problem of High Voltage Insulator flash-over due to accumulation of pollutant on insulators and if a possible solution could be found.
The assignment did not aim at identifying design concepts but, at this stage, at identifying feasible research paths which could lead to design concepts. Because of the confidential nature of the assignment, only partial results will be presented here.

Below, the process of problem-driven approach that has been followed which considers the consultation of the GB-BID database on separation to carry out the biological search:

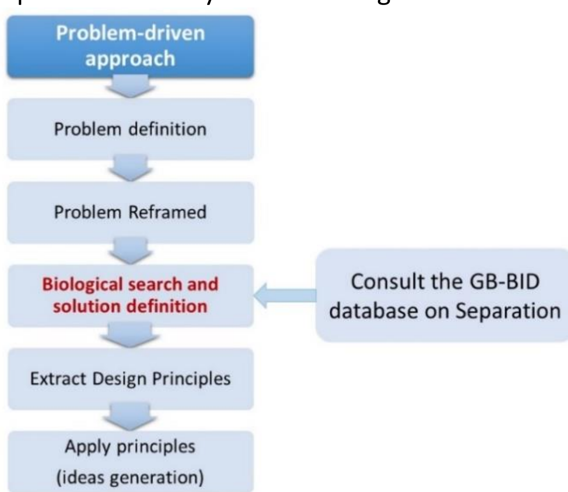



*Figure 8-28: Problem-driven approach followed to identify research paths to solve the problem of flashover in High Voltage Insulators.*

#### *Problem Definition*

High Voltage (HV) Insulators are used to insulate supports used to attach electric power distribution or transmission lines to utility poles and transmission towers. They support the weight of the suspended wires without allowing the current to flow through the tower to ground. Primary functions of an HV insulator are therefore:

**1) to support mechanically** the cables of the electric lines in order to create and maintain an air gap between the lines and the ground. The length of air gap depends primarily on system voltage, modified by desired safety margin, contamination level, etc. Another primary function is indeed.
**2) to insulate electrically** between the suspended electric cable and the metal components of the transmission/distribution tower. (Braini 2013)

The HV insulators are broadly divided into two types based on the material used. One is ceramic and the other is polymer (composite) insulator. Traditionally ceramic insulators of porcelain are used in both transmission and distribution lines. Now polymer or composite insulators are increasingly used in high voltage transmission systems.

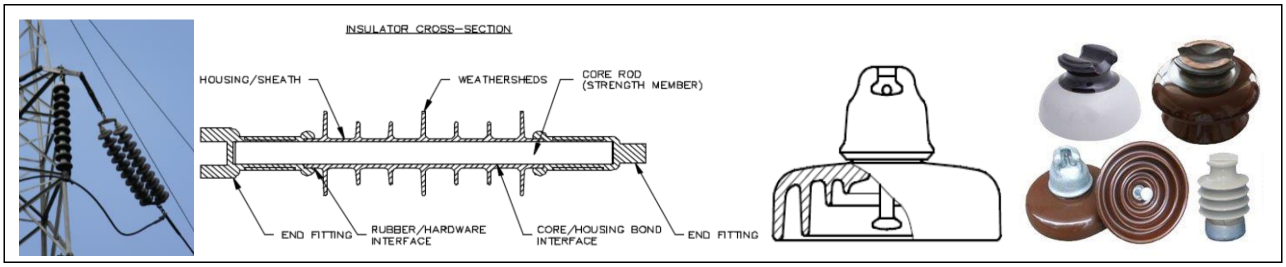
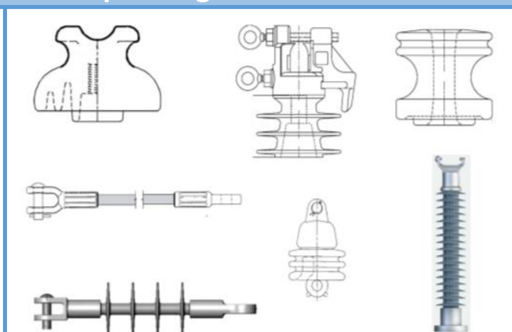
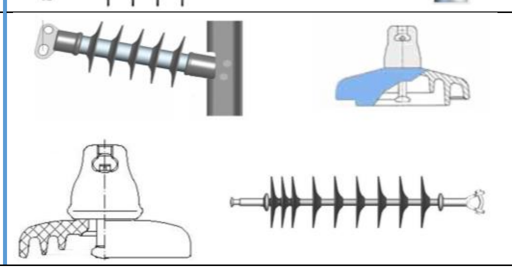



*Figure 8-29: Section of a composite insulator and traditional ceramic one. From (Braini 2013) and (Schwalm 2010)*

In Table 8-13 below an overview of typology of HV insulators in power grids:

| Currently more used type on Insulators in power grids | | |
|---|---|---|
| **Distribution lines** | • Pin type insulators -mainly porcelain, growing use of polymeric (HDPE – high density polyethylene), limited use of glass<br>• Line post insulators – porcelain, polymeric<br>• Dead end insulators – polymeric, porcelain, glass<br>• Spool insulators – porcelain, polymeric<br>• Strain insulators, polymeric, porcelain |  |
| **Transmission lines** | • Suspension insulators - new installations mainly Non-ceramic Insulators (NCI), porcelain and glass now used less frequently<br>• Line post insulators – mainly NCIs for new lines and installations, porcelain much less frequent now |  |

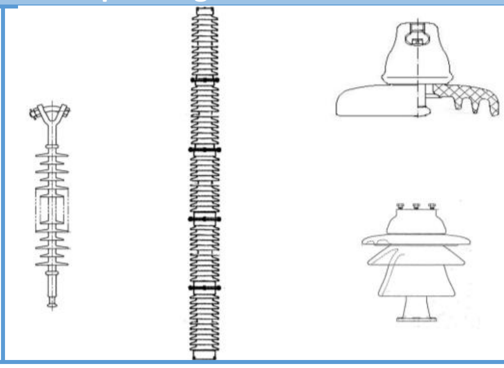
| Currently more used type on Insulators in power grids | | |
|---|---|---|
| **Substations** | • Post insulators – porcelain primarily, NCIs growing in use at lower voltages<br>• Suspension insulators –NCIs (primarily), ceramic<br>• Cap and Pin insulators |  |

*Table 8-13: List of currently more utilized types of Insulators in power grids with their picture or drawing. From (Schwalm 2010).*

HV Insulators are subject to occasional flashovers. One of the main reasons leading to the occurrence of flashover is ***dry-bands formation***. This is due to a synergy of factors: air pollutants (soots, salts and dust), air moisture (humidity, fog, and rain), temperature and winds (Ramos Hernanz et al. 2006).

Independently of the existing pollution type, the usual phases in which a flashover can appear in the insulator due to pollution are the following:

1. The pollution is placed on the surface of the insulator and a contaminant layer appears. The pollution can be caused by a great variety of sources, (sea salt, industries, ashes…). The wind is the main bearer of the particles, having a secondary role the gravity and the electric field.
2. By the action of rain, fog, etc. water droplets closest to the HV electrode causes substantial increase in the electric field that could lead to electric discharges. However, the maximum electric field is reduced as the droplets join together to form bigger droplets (to be expected due to the inverse relationship of the electric field with the radius of curvature of the water droplet). Induced charges within the droplet experience a strong electromagnetic force that causes the hemispherical shaped droplet to flatten and extend in the direction of the electric field, thus covering a wider surface area. As the silicone rubber coating of insulators loses its hydrophobicity due to electric field intensification, its surface will be covered with a conductive layer which permits the initiation of leakage current along the conductive path.
3. The flow of leakage current results in resistive heating and leads to drying of the wet layer on the insulator. As also the contaminant layer dries, dry-bands form and there is a further increase of conductivity and leakage current. These dry bands are likely to become visible on the smallest circumferential region where the current density is highest and partial electric arches appear through the dry bands.
4. Electric discharges gradually elongate as the dry regions widen and may extend over multiple dry bands and join with other electric discharges to form intense electric discharges which eventually bridge the whole insulator with a flashover. (Braini 2013)

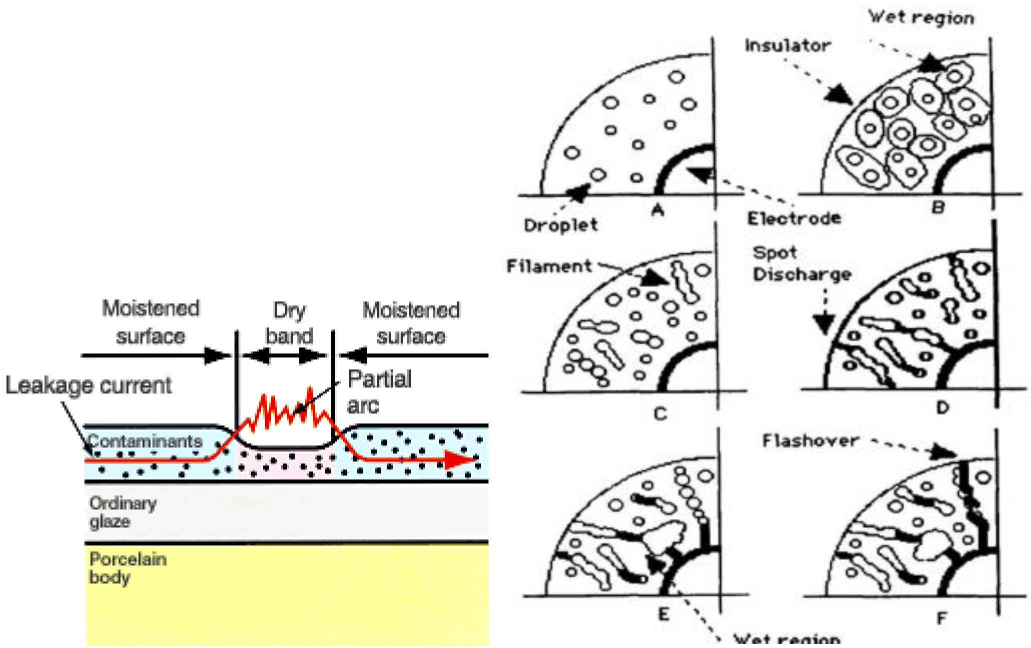



*Figure 8-30: Dry-band formation process and effect on leakage currents of dry-band producing partial electric discharge arc. From (Braini 2013)*

The performance of the HV insulator in carrying out its insulating function is however hindered and compromised by several factors which occur regularly with certain predictable frequencies as well as randomly. In order to respond to these factors, an insulator has also to carry out sub-functions which enable the fulfilment of its insulating function. Below, Table 8-14 highlighting the problems and cause-effect relationships identified as well as the sub-functions an insulator has to carry out to counter-effect the problems.

| Problems | Causes description | Effects | Enabling Sub-function |
|---|---|---|---|
| **Excessive Heat (generated by electricity)** | Leakage currents, electric fields, corona discharges generate heat in parts of the insulator by virtue of the resistance to the flow of electricity. | Deterioration of material mechanical and insulating properties, formation of | **Resist/Dissipate heat** |
| **Biological degradation** | Due to microorganisms colonizing the surface in the form of biofilm (algae, fungi, lichen). (mainly on polymer insulators) | Fouling masking hydrophobicity or increasing surface conductivity<br>Corrosion of components<br>Hydration | **Defend from biotic factors** such as algae, fungi, lichens |
| **Air pollutants accumulation** | Sulphur dioxide from industries emission, Ozone and NO2 (produced by corona effect) reacts with water to form HNO3. Salts (including NaCl) present in aerosol in coastal areas. Dusts, fertilizers, Fly-ash, industrial smokestacks | Insulators produce turbulence in airflow, which results in the aerodynamic 'catch' and deposition of particles on their surfaces causing: Formation of conductive layers, Corrosion.<br>All the above leading to electrical breakdowns and flashovers | **Avoid air pollutants settling** |

| Problems | Causes description | Effects | Enabling Sub-function |
|---|---|---|---|
| **Environmental stresses/Weather conditions** | UV exposure;<br>Temperature variations Ice/snow deposition<br>Rain and fogs | Tracking and erosion (leading to hydration)<br>Acceleration of the rate of oxidation with deterioration of hydrophobic material;<br>UV causes mechanical and chemical degradation of the polymer structure.<br>Deposited rain and fog can generate leakage currents and facilitate formation of dry bands<br>Sand can erode polymers and compromise hydrophobicity | **Defend from abiotic factors:** such as wind, rain, fog, sandstorm, snow, UV |
| **Impacts due to combination of pollutants with adverse weather conditions** | Combination of contaminants and moisture due fog or rain on the surface of the insulator.<br>Dirt, pollution, salt, and particularly water on the surface of a high voltage insulator can create a conductive path across it, causing leakage currents and flashovers. | Dry bands formation, dry discharges and subsequent occurrence of Flashover<br>Material deterioration due to heat generated by leakage currents/electric breakdowns as well as UV by dry discharges | **Reduce leakage currents/electrical breakdowns**<br><br>**Resist/Dissipate heat**<br><br>**Defend from abiotic factors** |
| **Atmospheric electricity/ O&M faults** | Atmospheric electricity due to storms, Lightning strikes<br>Electrical faults | These phenomena can generate leakage currents and flashovers and extreme heat in materials | **Reduce leakage currents/electrical breakdowns**<br>**Resist/Dissipate heat** |

*Table 8-14: Problems, cause-effects and enabling sub-functions. Drafted by the researcher on the basis of (Amin M. 2006), (Braini 2013) , (Schwalm A. et al. 2010), (Ramos Hernanz et al. 2006).*

In order to respond to each of the aforementioned problems via enabling sub-functions several solutions have been developed. A summary table is proposed below (Table 8-15).

| Enabling sub-function | Existing Solutions | Details/Comments |
|---|---|---|
| **Resist/Dissipate heat** | • Heat resistant material<br>• Heat dissipating shapes and surfaces | • Heat resistant materials;<br><br>• Corrugated surfaces (notches) which facilitate heat dissipation or prevent heat concentration |
| **Defend from biotic factors** | • Coatings with different chemical products<br>• Active cleaning | • Insulator made from a mixture of organic and inorganic materials;<br>• Flame retardant to suppress fungal growth;<br>• Biocides to inhibit the reproduction of microorganisms;<br>• Periodical cleaning and decontamination (manual/automatic); |
| **Avoid pollutants settling** | • Use of more self-cleaning material by virtue of low surface energy and hydrophobicity (non-wettable material)<br>• Active cleaning | • Use of hydrophobic coatings or polymeric housing insulators which are more hydrophobic and therefore allow water droplets removing accumulated pollutant;<br>• Periodical cleaning and decontamination |
| **Defend from abiotic factors** | • Adapt design<br>• Use suitable material<br>• Active cleaning | • Prevention of ice bridging across sheds through large shed-to-shed separation;<br>• Reduction of total ice accumulation, often through reduced insulator diameter; |

| Enabling sub-function | Existing Solutions | Details/Comments |
|---|---|---|
| | | • Promotion of natural ice shedding through smooth surface finish or semiconducting glaze;<br>• Use of hydrophobic silicon coating;<br>• UV resistant material;<br>• Periodical cleaning and decontamination. |
| **Reduce leakage currents/electrical breakdowns** | • Shapes which Increase creepage length<br>• More effective water draining shapes<br>• Active Cleaning periodically<br>• Creepage extenders<br>• Protection with RTV (Room temperature vulcanizing) , HTV (High Temp. Vulcan.) Silicone housing and coatings<br>• Protection with Oil and Greases coating<br>• Use of Polymeric materials (silicone rubber/EPDM) to increase hydrophobicity<br>• Semiconducting glaze which divert leakage currents<br>• Shapes and surface micro/nano textured which protect surfaces from contamination<br>• Arching horns to by-pass flash-over | • Increase the leakage distance, to ensure that dry band formation and surface arcing is minimized: a) by adding insulator sheds<br>b) Longer leakage path design;<br>• Rounded edges to avoid charges accumulation at sharp edges;<br>• "Umbrella" shaped to allow quick drainage of water;<br>• Cover with thin layer of RTV or HTV silicon to provide hydrophobicity (and restored hydrophobicity following contamination);<br>• Use of water droplet + hydrophobicity of housing material to remove dust particles from surface. Hydrophobicity can be temporarily lost due to contaminant layers and dry bands formation<br>• Periodical cleaning and decontamination;<br>• Extra extension of sheds to extend the tested flash-over voltage;<br>• Thin layer of petroleum or silicon grease (this last not used anymore) to improve resistivity and trap dust particles in grease avoiding dry-bands formation;<br>• Porcelain insulators covered with layer of semiconducting material (ex: tin-oxides) which channel leakage current in dry-bands to avoid partial discharge with arcs;<br>• Self-cleaning + Super-hydrophobic coatings and textures. |

*Table 8-15: Existing solutions for enabling sub-functions of HV insulators.*

However all the above solutions do not necessarily remove the problems but delay them or allow to better monitor their occurrence. The solutions are also temporary and imply costs to be maintained.
Are there different and more promising solutions to be set in place in order to reduce flashover occurrence? Can we prevent pollution to settle on insulators?
The objective of this study was to provide the client with an analysis of the problems/solutions with a bio-inspired approach and recommendations on possible research paths aiming at developing more effective solutions.

### *Problem reframed and Biological Search consulting the GB-BID Database for Separation*

From the problem analysis, the functional analysis would suggest to explore natural strategies carrying out the following actions:

| **Enabling Sub-Functions** (as per Table 8-15**)** | **Natural Strategy's actions** |
|---|---|
| Defend from biotic factors | repel, deflect, regulate adhesion, transform, inhibit |
| Defend from abiotic factors | repel, deflect, regulate adhesion, transform |
| Avoid pollutants settling | repel, deflect, regulate adhesion, transform |
| Resist/Dissipate heat | resist/dissipate (heat) |
| Reduce leakage currents/electrical breakdowns | insulate, optimize (surface/volume ration) (to increase creepage distance) |

*Table 8-16: Natural strategy's actions to be explored on the basis of the functional analysis of the problem.*

The GB-BID database was partially utilized searching for actions such as “repel”, “separate”, “deflect” and “transform”. Only “repel” and “deflect” (which could also be considered strategy actions of main function “regulate adhesion”) provided relevant solutions. Below, in Table 8-17, the solutions identified from the GB-BID database:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Separation Principle |
|---|---|---|---|---|---|
| **Lotus** | **Leaf** | Repel | Water/particles/oil | Air | Surface tension regulation via micro/nano morphology |
| **Shark** | **Skin** | Repel | bacteria/organisms | Water | Adhesion and Surface tension regulation via micro morphology and vortexes |
| **Spiny Dogfish** | **Skin** | Repel | Oil, organic liquids / skin | Water | Surface tension regulation via micro morphology |
| **Rosa montana** | **Petals** | Repel / attract | Water | Air | Surface tension regulation via micro morphology |
| **Viola tricolor** | **Petals** | Repel | Water | Air | Surface tension regulation via micro morphology |
| **A. bindusara (cicada)** | **wings** | Repel | Water | Air | Surface tension regulation via micro morphology |
| **M. opalifer (cicada)** | **wings** | Repel | Water | Air | Surface tension regulation via micro morphology |
| **C. atrata (cicada)** | **wings** | Repel | Water | Air | Surface tension regulation via micro morphology |
| **Leafhoppers (cicadellidae)** | **wings** | Repel | Water/oil | Air | Surface tension regulation via micro morphology |
| **Collembola (springtail)** | **Body** | Repel | Water & Oil | Air | Surface tension regulation via micro morphology |
| **Colocasia esculenta (Taro)** | **Leaf** | Repel | Water | Air | Surface tension regulation via micro morphology |
| **Mammals** | **Eyelashes** | deflect | particles/ moisture | Air | Deflection via vortexes created by structures |
| **Desert Scorpion** | **Skin** | deflect | particles | Air | Deflection by surface micro morphology |

*Table 8-17: Result from filtering the GB-BID database in the fields “main action” using respectively keywords: repel/deflect. Also indicated the medium and the separation principle.*

From the organisms selected above the following range of solutions can be extracted:

- Super-hydrophobicity or super-hydrophilicity repelling or attracting polar liquids (such as water) by regulating surface energy and contact areas;
- Oleo-phobicity or oleo-philicity in air or water;
- Self-cleaning property by using roughness which prevent external particles to settle and their subsequent removal via water droplets (combined with super-hydrophobicity property);
- Self-cleaning property by using roughness generating useful micro turbulences (of air and water) removing/deflecting dirt in close proximity of the surface (µm range);
- Anti-bacterial properties by using roughness with obstaculates bacteria settling;
- Anti-erosion properties by roughness deflecting impacting particles.

Furthermore, a similar search was carried out in the database using complementary actions such as: “attract”, “trap”, “extract”, “condense” in order to find solutions which could act not *on* the insulator but *externally*, as a barrier to insulator. Alike sacrifical devices, they could divert the problem from the insulator and make it more manageable at lower cost. Below (Table 8-18) the solutions identified from the GB-BID database:

| Biological Organism | Phenotype | Main Action | Object - What is Separated | Medium | Separation Principle |
|---|---|---|---|---|---|
| **Cacti** | **Spines** | Extract | Moisture | Air | Phase change - Coalescence of droplets |
| **Tillandsia Lanbekii** | **Leaf** | Extract | moisture | Air | Phase change - Coalescence of droplets |
| **Cotula fallax** | **Leaf** | Extract | Moisture | Air | Phase change - Coalescence of droplets |
| **Desert geophytes** | **Leaf** | Extract | Water | Air | Phase change - Coalescence of droplets |
| **Flying saucer trench beetle** | **Behaviour** | Extract | Moisture | Air | Phase change - Coalescence of droplets |
| **Elephant seal** | **Respiratory system** | Extract | Water | Air | Phase change Condensation/evalopration |
| **Syntrichia caninervis** | **Leaf** | Extract | Water | Air | Phase change - Coalescence of droplets |
| **Tubeworms** | **Housing** | Extract | Ions | Water | Phase change - biomineralization |
| **Camel** | **Respiratory system** | Extract | Water/moisture | Air | Phase change - condensation |
| **Namibian Desert beetle** | **Body surface** | Extract | Moisture | Air | Phase change - Surface tension regulation |
| **Tick** | **mouth** | Extract | Moisture | Air | Phase change - Hygroscopic material |
| **Lichens** | **Leaf** | Extract | Water | Air | Phase change - Coalescence of ice |
| **Rosa montana** | **Petals** | Repel / attract | Water | Air | Surface tension - regulation via micro morphology |
| **Fagus sylvatica** | **Leaf** | Attract | Water | Air | Phase change - Surface tension regulation via micro morphology |
| **Magnolia grandiflora** | **Leaf** | Attract | Water | Air | Phase change - Surface tension regulation via micro morphology |
| **Pitcher plant** | **Tissues - Peristome** | Attract | Water | Air | Phase change - Surface tension regulation via micro morphology |
| **Namib Desert Grass** | **Leaf** | Extract | Moisture | Air | Surface tension regulation via micro morphology |
| **Nolana Mollis** | **Leaf** | Extract | Moisture | Air | phase change - Osmotic potential |
| **Cribellate Spider** | **Silk web** | Extract | Water/moisture | Air | Phase change - Coalescence of droplets |
| **Saiga** | **Respiratory system** | Extract | Water/particles | Air | Phase change/Surface Dead end filtration/Contercurrent heat exchange |

*Table 8-18: Result from filtering the GB-BID database in the fields "main action" using keywords: attract/trap/extract/condense. Also indicated the medium, the separation principle.*

As one range of solutions already utilized in HV insulators is to provide shapes (not only materials) that allow for fast drainage of droplets, the GB-BID database can be also consulted filtering for the sub-action+object "*move liquids*". Around 30 organisms can be extracted (see sample in table below) whose separation mechanisms also involve strategies for moving fluids passively and actively. From these strategies additional relevant design principles could be extracted (Table 8-19).

| Biological Organism | Phenotype | Sub-Action 1 | Object of sub Action1 |
|---|---|---|---|
| **Desert geophytes** | **Leaf** | Move | Liquids |
| **Shark** | **Digestive systems** | Move | Liquids |
| **Birds** | **Respiratory system** | Move | Air |
| **Sponges choanotyces** | **Feeding system** | Move | Liquids |
| **Blue mussel** | **Gills** | Move | Liquids |

| Biological Organism | Phenotype | Sub-Action 1 | Object of sub Action1 |
|---|---|---|---|
| **Thorny devil** | **Body surface** | Move | Liquids |
| **Shark** | **Skin** | Manage | Liquids |
| **Bowhead Whales** | **Feeding system** | Move | Liquids |
| **Humpback Whale** | **Feeding system** | Move | Liquids |
| **Manta ray** | **Feeding system** | Move | Liquids |

*Table 8-19: Result from filtering the GB-BID database in the fields "sub-action+object" using the keywords: move+fluid.*

### *Extracting Design Principles*

From the biological solutions identified several design principles have been extracted which could be utilized to design insulator surfaces and shapes which enhance self-cleaning processes by reduced adhesion or pollutants deflection:

1. Create isotropic or anisotropic micro/nano textures on surface made of one or 2-orders hierarchical structure of pillars with dimension, geometry and density which activate low adhesion and super-hydrophobic behavior at the interface solid/air/water.
2. Create micro textures grooves on surfaces with groove distance (D) = 2 mm; groove width (W) = 5 mm; groove height (H) = 4 mm which avoid deposition and erosion by sand.
3. Create anisotropic textured surface with nano-ridges filled with a gel medium. Larger bio-foulers are excluded from the surface by the roughness and can be flushed away by water flow. Smaller adhesive molecules are excluded from the surface by the properties of the gel.
4. Create surface with longitudinal ridges that run parallel at irregular distance (ca.15-115 µm) to each other, with some ridges more predominant than others.
5. Apply barriers made with arrays of fibres/filaments disposed at specific intra-distances which generate turbulent air passages blocking /diverting suspended particles.
6. Apply barriers, external to the insulators, which can attract moisture and pollutants diverting them from the insulators.
7. Design convoluted, spiralling shapes of insulators which speed up water drainage process.

Specific design concepts have not been developed yet based on the above principles.

### *Conclusion of the case study*

The value of this case study is not much in the design solutions identified, which for the time being remain at the level of design principles and possible research paths. The value lies on the following aspects:

- It demonstrates that the GB-BID database on separation can be utilized also for problems not related to the Separation Technology sector, but related to the broader definition of "separation" where two or more elements need to stay separated by mean of regulating adhesion.
- It showed how the GB-BID database on separation could be connected with another GB-BID database on functions such as "regulate adhesion" or "move liquids". Databases which could provide further bio-inspired design principles to optimize forms of HV insulators in order to increase their self-cleanliness and capacity for heat dissipation, so increasing their insulating capacity without compromising their other main function which is to support mechanically.
- Following a literature review and discussion with the firm requesting this study, it seems that this is the first time that a BID method has been applied to the specific sector of HV insulators.

## 8.6 Conclusion of the Chapter

As per Chapter 7, the specific research question investigated in this chapter was:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

The case studies proposed in this chapter and developed using the GB-BID database on separation allow giving an affirmative reply to the research question as they demonstrate that:

- **At Sector Level**: from the GB-BID database it is possible to extract broad (deep) design principles related to separation mechanisms and separation structures which could be utilized to take strategic decision on which research path to follow when trying to solve separation problems. This was highlighted with two examples (spacers of RO membranes and falling film evaporators).
- **At Sub-sectors Level**: A similar process of extraction was carried out to generate Taxonomies of biological strategies organized according to major problems of separation expressed in terms of *action+object+object's properties* and *process conditions*. The utility of the taxonomies was tested during the ideation workshop with knowledge-based experts receiving good feedbacks.
- **At Context-driven Level**: via two examples of product development: the Mangrove Still and Bio-Cover, it has been demonstrated how the GB-BID database can be utilized to generate feasible design concepts to solve specific and diverse problems related to separation. Both case studies reached the prototyping phase providing promising results. The *Mangrove Still* is currently in a scaling-up phase thanks to EU H2020 funding and the *Bio-Cover* has been further assessed within another EU funded project led by Whirlpool (results are confidential).
- **Across-Sectors Level**: the case study related to the problem of the flashovers in High Voltage insulators demonstrated that the GB-BID database for separation can also be utilized to solve problems not directly related to Separation Technology sector. This allows expanding the benefit of the GB-BID method and therefore reducing the cost/benefit ration.

# 9. CONCLUSIONS

## 9.1 Summary of the research

Based on the State-of-the-art of BID and Innovation models, which highlighted issues to be addressed in order to increase the diffusion of BID into the business environment (section 2.2.6 and 2.3.5), the Research Question distilled was:

***How should a BID method/Tool be designed and utilized in order to generate bio-inspired ideas more likely to become innovation in business environment?***

To answer the above broad question, two sub-questions were formulated:

1. *Which framework of innovation model would enhance the synergy between BID and the Innovation process so as to increase the effectiveness of BID as tool for innovation?*

2. *Which type and amount of biological information should be considered in a BID tool and how to structure it so as to increase the effectiveness of the BID process in terms of ideation metrics?*

In order to answer the sub-questions, two main methodological approaches were followed:

- Explore the natural evolutionary process and, by analogy, extract design principles to formulate innovation models more aligned with natural principles where the ideation process is a continuous multi-stakeholders participative process (section 4.3.6);
- Review literature on BID to identify key factors affecting BID effectiveness and based on these, extract possible solving strategies (section 3.2.3) which led to the formulation of BID methods' Design Principles. Designing BID methods following these principles may increase the effectiveness of BID and facilitate its introduction in the business environment.

On the basis of the above, answers to the research sub-questions were proposed:

- The *Evolutionary Innovation Model,* (section 5.1.1) which is a framework for a Coopetitive/Open Innovation model; this is proposed as conceptual answer to sub-question n.1;
- The *Guild-base* (or *Sectoral*) *BID method (GB-BID),* (section 5.3) which consists in a method to set up databases of biological solutions to be used to generate bio-inspired ideas of interest by industrial practitioners within a specific industrial sector. This is proposed as operative answer to sub-question n.2 which went through testing and validation procedure.

In order to test and validate this BID method the following refined research question had to be answered:

*Can the BID method and tool proposed, increase the effectiveness of the BID process in terms of ideation metrics?*

As the GB-BID method foresees a sectoral approach, the sector of *Separation Technology* was selected to prepare the GB-BID Database for testing. Testing and validation has been carried out via Ideation Workshops and Case Studies. The procedure led to the following conclusions:

The *Ideation workshops* confirmed that the GB-BID method:

- Allows producing bio-inspired ideas with calculated ideation metrics similar to other BID methods such as AskNature and SBF-DANE. (see sections 7.3, 7.4, 7.6)
- Can be successfully used by multi-disciplinary teams including non-technical experts. (see section 7.3)
- Within the specific setup of the workshops carried out and according to their results in terms of ideation metrics, the cost to set up a GB-BID Database may not be justifiable considering the existence of AskNature as an open source database.
- Is compatible with a sectoral approach to innovation where knowledge-based experts cooperate (see section 7.5). It is therefore compatible with the Evolutionary Innovation Model.

The *case studies* confirmed that the GB-BID method:

- Allows extracting broad design principles which can provide valuable indications to evaluate existing technology vis-à-vis natural principles and steer sectoral research toward innovative solutions (see section 8.2). These could have not been extracted with other existing and accessible biological repositories (such as AskNature and Find-Structure).
- Allows to produce taxonomies of “robust” (with a certain frequency of occurrence in Nature) biological solutions which could be utilized to evaluate existing technology vis-à-vis natural principles and to generate innovative bio-inspired ideas. This type of information has been also highlighted as relevant by knowledge-based experts during ideation workshop (see sections 8.3, 7.5). These could have not been extracted with other existing and accessible biological repositories (such as AskNature and Find-Structure).
- Allows producing various and novel design concepts for solving separation problems which can become marketable innovation and competitive with existing solutions (see section 8.4).
- Allows producing bio-inspired ideas for industrial sectors different from the one for which the GB-BID database was originally generated (see section 8.5).

Based on the above results, the researcher concludes that the refined research question has been affirmatively answered even if further tests should be undertaken in order to confirm the effectiveness of the GB-BID method in ideation works compared with other existing BID methods/tools. This to justify the cost for setting it up compared with already existing and free of charge BID tools and biological repositories (in particular AskNature).

## 9.2 Overall Conclusions

The research explored issues which influence the effective utilization of BID in the business environment. Based on this exploration, solutions have been proposed to increase this effectiveness.
The solutions provided are: the concept of *Evolutionary Innovation Model* and *the Guild-based* (or *Sectoral*) *BID method*.
The main features of these proposed solutions, which differentiate them from already existing Innovation models and BID methods are:

- Sectoral: both solutions are conceived to be customized for specific industrial sectors and assist firms belonging to each sector in their endeavour of innovating products.
- Open: the solutions are conceived to promote Open Innovation/Coopetitive models (the EIM) and to be effective within these models (the GB-BID method) so as to allow sharing of costs for a BID approach to innovation as well as benefits with other firms (including competitors).
- Problem-based: in the GB-BID database, biological information are retrieved and processed so as to be meaningful and useful for specific target groups (sectors) with specific problems. In this way cost/benefit ration could be more favourable to justify investment in a BID approach to innovation.
- Multi-levelled: thanks to its amount of biological solutions and the possibility to identify their "robustness", the GB-BID database is able to advice at different levels; for instance identifying bio-inspired research paths worth pursuing, evaluating existing technology vis-à-vis robust biological solutions and generate bio-inspired design concepts for specific products working in specific operating conditions.
- Inclusive: the GB-BID database provides biological information in formats which can allow participation to the ideation process also on non-technicians (ex: firm's managers).

The results achieved so far by this research give indication that a BID method/tool with the above features can indeed be beneficial to the industrial environment. Features which are not explicitly present in other BID methods/tools. This however does not mean that other BID methods could not be tailored to embed these features. This aspect could be explored in further research activity.
It needs to be emphasized that the GB-BID method does not exclude the use of other existing BID methods and tools, either as complementary (ex: prepare and utilize biological models according to SBF or SAPPhIRE ontologies) or integrated (consult AskNature to start feeding up the GB-BID Database).

The ideal vision for the utilization of both EIM and GB-BID method is the one where groups of firms operating in the same sector and connected both in a supply chain and as competitors decide to setup Open Innovation/Coopetitive schemes to invest resources in creating GB-BID databases and share it to generate, individually or in synergy, bio-inspired innovative ideas.

## 9.3 Major limitations of the research

- Because of the multidisciplinary nature of this research, the researcher, despite his background, had to expand his knowledge in several domains in a relatively short time. In doing this, the accuracy of explanation of facts and processes may have suffered. In particular exploring biology in such a broad range of topics (all biological levels engaged in evolutionary processes and organisms dealing with separation processes) was rather overwhelming and biological information extracted, despite partially cross-checked by two biologists may be affected by a subjective judgement and mis-interpretation.
- Some difficulty in organising ideation workshops, especially outside academic environment, leads to carry out workshops in far-from-ideal set up where participants were not enough to generate robust statistics, their motivation was uncertain and where time constraints affected the absorption of information and the generation of ideas. These factors may have had an effect on the metrics of ideation preventing to detect differences in performance among the BID methods tested.

- Because of the intent of the GB-BID method to be more usable by the industrial/business environment, the difficulty in testing it with a higher number of knowledge-based experts has been particularly penalizing.

## 9.4 Originality of the research

The works carried out in this research are considered original because they aim at tackling some issues not often investigated in researches around BID:

- The connections between BID and Innovation process in business environment, trying to enhance the synergy between these two domains and increase the effectiveness of BID as tool for innovation.
- Which general principles could be followed to design more effective BID methods and tools.
- Which type of biological knowledge should be considered in a BID tool and how to present it in order to maximize the benefits of the BID process compared to its cost.

In terms of research methodology, an original element has been the *use of BID approach as research methodology***;** BID is usually utilized to generate ideas for products and processes. In this research, it has been utilized as a research methodology to research on Innovation methods and systems. To the best knowledge of the researcher, this has not been attempted before.

## 9.5 Importance of the research

This research is considered relevant from a scientific and industrial perspective because:

- It is multi-disciplinary. Several domains, far from each other, have been consulted and connected such as Biology (Ecosystem dynamics, Evo-Devo, Animal and Plants Physiology), Innovation (Process, Management, Systems), Design (BID) and Separation Technology;
- It explores biological analogy at evolutionary and ecosystem level. BID rarely focuses on biological analogies at those level because of their complexity, the still lack of consolidated theories and difficulties in transferring meaningful principles by non-biologists.
- It connects BID with Innovation and industrial/business environment. Connecting BID with the very actors of innovation, the chances of enhancing the potentiality of BID and diffusion of its utilization increase.
- It suggests new paths for research in BID methods and innovation models. Paths in which the cost/benefit ration of BID should also be considered.
- It sets the basis for stimulating bio-inspired innovation in the sector of Separation Technologies: the case studies such as deep biological principles and the taxonomy of biological solutions can be already utilized to generate bio-inspired ideas in the sector.

## 9.6 New Knowledge produced

The researcher believes that the research produced new knowledge. In particular:

- A framework of principles to formulate BID methods and Innovation models, which are compatible with each other, to be further developed and tested (sections 5.1).

- A systemic perspective of evolutionary processes which could assist in utilizing biological analogies at system level (Figure 4-6).
- An eco-systemic perspective of innovation aiming at improving the current analogy (Figure 4-7).
- A preliminary set of deep biological principles for separation which could be used to frame research for innovative separation technology products (see section 8.2).
- A preliminary taxonomy of biological solutions for separation which could be already used to generate ideas for innovative separation technology products (see sections 8.3).
- Two innovative design concepts for separation technologies (see sections 8.4.1 and 8.4.2), prototyped and tested one of which is currently under up-scaled pilot testing in the real conditions.

## 9.7 Follow-up

The preliminary results of this research should be reviewed and expanded through the following activities:

- Review of the fields of the GB-BID database on separation by knowledge-based experts to confirm its validity and to identify new parameters which could be introduced to increase its usefulness to the sector (for instance “scalability”, as mentioned in section 7.6).
- Review the biological knowledge introduced in the GB-BID database for separation by biologists in order to remove mis-interpretations and further validate it.
- New experiments should be carried out for testing the ideas generation potentiality of the GB-BID database vis-à-vis other BID methods. The new set up should consider: larger samples to produce more robust statistics, longer duration of the experiment where more biological solutions are utilized to generate ideas (more than the eight utilized in this research) and different sets of problems to be solved (different complexity and topics) to test the sensitivity of the method to the problem.
- The GB-BID database should be tested in industrial environment and in a set up compatible with the principles of Evolutionary Innovation Model.
- Another GB-BID database should be set up in order to test the connection among GB-BID databases and their effectiveness to generate cross-sectoral ideas.
- Another existing BID method should be modified in order to embed the same features of the GB-BID method but within its own ontology. Experiments should then be conducted to assess the difference in performance between this modified BID method and the GB-BID one to determine the effect of different organization of information on the performance.

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