ANNEX 1 - Analysis of the Context (Innovation Process/Management and BID)

Table of Contents

LIST OF FIGURES

LIST OF TABLE

A. About Innovation process and management

1.A.1 Innovation process

Innovation, widely recognized as essential condition for business success ensuring growth, competitiveness and possibly sustainability, 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). From a general point of view innovation can be considered *a process* (a process to be managed) which bring an idea to the market as a new product, process or service through the phases of idea generation, research and development, product development and commercialization.

An important distinction to be made is between Ideas and Inventions. The idea becomes an invention, when it is converted into a new useful, viable and feasible artefact. The inventions are necessary seed for innovations, but the inventions do not inevitably lead to the innovation (Trott, P. 2008; Varjonen, V. 2006). As a consequence also another distinction should be made between innovation and invention. According to this different degrees of "novelty", innovations do not necessarily represent something entirely new, while invention does (Tabas, et al., 2010). We can understand innovation as a way of transforming the resources of an enterprise through the creativity of people into new resources and wealth. (Ondrej Zizlavsky 2014). Irrespective of the type of innovation, the starting point is an innovation idea starting with a new insight of a single individual (Björk and Magnusson 2009).

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, it was utilized as starting point the analysis made by Baregheh et al. (Baregheh, Rowley, and Sambrook 2009). Through literature review from different disciplinary areas the authors identified six recurring attributes that are included in diverse definitions of innovation (60 definitions were collected). Additional attributes and words have been identified as resulting from the review of additional papers and book concerning innovation process management. The Table 0-1 below, expanded and adjusted on the one presented by Baregheh et al. (additions highlighted in green colour) presents these attributes including the words which more frequently have been associated to a specific attribute.

Attributes	Words associated with attributes	Description
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.*
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.*
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
Inputs (Means)/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*
Aim	Competition, Success, Economy Superiority, Differentiation, Advantage, Value	*Refers to the overall result that the organizations want to achieve through innovation.*

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*
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.*
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*
Impact	Disruptive, Sustaining, Sustainable, Social, Inclusive	*Refers to the effect that the innovation has (purposefully or not) on the outside World (people and environment)*

Table 0-1: Attributes of Innovation by Baregheh et al. - revised by the researcher (in green)

These attributes, excluding “Aim”, “Social” and “Inputs/Outputs” which are not considered relevant to be further expanded for the research, are described in details in the following sections and will allow formulating a more organic framework of the Innovation process.

1.A.2 Innovation process’s stages

As 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.

If an innovation idea starts with a new insight of a single individual (Björk and Magnusson 2009), who are these individuals and where are they? The following categories have been identified (Tidd J. , Bessant J. 2014):

- **Individual Inventors**: these are often small teams and rarely single individuals (Lemley, Mark A., 2011) who investigate a certain problem an propose solutions developed without having an established organization.
- **Universities/Research Centres**. These are traditionally the source of knowledge creation which can be the basis of innovative ideas. Starting from basic to applied research and their promotion via scientific publications, Universities and Research Centres receive funding mainly from public institutions but also from private ones engaging in collaboration with firms on specific projects.
- **SMEs and large Industry**. These are the main actors in innovation process as it is their purpose to innovate in order to compete in the market. Traditionally, companies’ research and development (R&D) departments is an important source of innovation. However R&D as a process has evolved from being closed to a single department within the firm, mono-disciplinary and under corporate control, to an open process involving internal as well as external entities (including competitors) and multi-disciplinary (Chiesa 2001)
- **Innovative Start-ups** The category of start-up has been differentiated because despite belonging to the business sector they are not usually engaged in a continuous process of innovation and production such as well-established SMEs and large firms. They are in their initial stage of developing and promoting a single type of innovation (product, process, service..). They often emerge as spin-off from Academic environment.

One relevant factor connecting these categories is *Technology Transfer*. Following the definition of UNIDO “*Technology transfer is the mechanism by which the accumulated knowledge developed by a specific entity is transferred wholly or partially to another one to allow the receiver to benefit from such knowledge”*(UNIDO 2004).

1.A.3 Type of Innovation

Below Table 0-2 describing the different types of innovation generated by the innovation process as described in (OECD 2002)

Type of Innovation	Description
Products	**Product innovation** is the development and introduction of a product that is new or significantly improved with respect to its characteristics or intended uses.
Services	**Service innovation** is the development and introduction of a service that is new or significantly improved with respect to its characteristics or intended uses.
Processes	**Process innovation** is the development and implementation of a new or significantly improved production or delivery method. Process innovations can be intended to decrease unit costs of production or delivery, to increase quality, or to produce or deliver new or significantly improved products.
Marketing methods	**Marketing innovation** is the development and implementation of a new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing. Marketing innovations are aimed at better addressing customer needs, opening up new markets, or newly positioning a firm's product on the market.
Business models	**Business model innovation** is the development and implementation of a new business model or the new implementation of a significant proportion of the existing business model.
Organizational methods	**Organizational innovation** is the implementation of a new organizational method in the firm's business practices, workplace organization or external relations. Organizational innovations can be intended to increase a firm's performance by reducing administrative costs or transaction costs, improving workplace satisfaction (and thus labour productivity), gaining access to non-tradable assets (such as non-codified external knowledge) or reducing costs of supplies.

Table 0-2: Different types of innovation. from (OECD 2002b)

1.A.4 The Nature of Innovation

Despite referring to Baregheh (Baregheh, Rowley, and Sambrook 2009) in clustering the concepts below, under the attribute "nature of innovation", other authors also refer to them as "degrees" of innovation to relate them to the level of "novelty" embedded:

Attribute	Description
Incremental *Continuous*	Incremental innovations build on existing knowledge and occur continuously in the organization. These innovations lead to small gradual improvements in products, services or processes which have generally quantifiable impact on the business (Ondrej Zizlavsky 2014). This degree of innovation is often associated with a **continuous** process of improvement which take place within an established framework (Björk, Boccardelli, and Magnusson 2010)
Radical *Breakthrough*	Radical innovations stem from the creation of new knowledge and the commercialization of completely novel ideas or products. It is about technological breakthrough. A radical innovation though may not necessarily become a disruptive

Discontinuous	one.(OECD 2002) (Tidd J. , Bessant J. 2014; Varjonen, V. 2006). This degree of innovation is also called by some authors **breakthrough** or **discontinuous** (Kishna et al. 2017; Björk, Boccardelli, and Magnusson 2010).

Table 0-3: Attributes related to the "nature of innovation"

1.A.5 The Models of Innovation

The literature regarding innovation models points essentially at the following ones which have been developed progressively in time - from which a categorization according to *generation* - but which are all still utilized nowadays despite a gradual shift toward more circular, networked ones:

Models of Innovation	Generation	Description
Technology Push	First	Simple *linear sequential* process. Emphasis on R&D and science. Innovation is pushed by technology and science
Market/Demand Pull	Second	Simple *linear sequential* process. Emphasis on marketing. Innovation is pulled by market needs.
Coupling	Third	Recognizes interaction between different elements and *feedback loops* between them. Innovation is a result of simultaneous coupling of knowledge within all three functions: R&D, manufacturing and marketing.
Interactive	Forth	Combination of push and pull models, integration within firm. Innovation process is viewed as parallel activities across organizational functions.
Network	Fifth	Recognizes influence of external environment and the effective communication with external environment. Innovation happens within a network of internal and external stakeholders. Example of networks are: communities of practice, sectoral networks, spatial clusters, internal project teams, etc.. Continuous innovation
Open Innovation	Sixth	Innovation processes does not take place only within the firm boundaries. Internal and external ideas as well as internal and external paths to market can be combined to advance the development of new technologies or introduction of innovative products, services and processes.

Table 0-4 Models of Innovation - Definitions from: (Tidd J. , Bessant J. 2014; Tidd 2006; Varjonen, V. 2006; Enkel, Gassmann, and Chesbrough 2009)

From the models highlighted in Table 0-4, it is worth noticing how the models developed through the years shifted from being linear and confined within a single to few innovation actors, close/internal therefore with a low level of complexity to models which are more non-linear/circular, open/external with many actors involved and therefore with an increased complexity.

Open Innovation Model

Chesbrough (Chesbrough 2006) defines Open Innovation 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 Open Innovation process therefore combines ideas and knowledge internal and external to the company in order to capture value from the outside.
Some other reasons pointed out by Chesbrough (2003b)(Del Giudice 2015) are as follows:

- Widespread circulation of useful knowledge
- Firms' inadequate exploitation of available information
- Loss of ideas that are not immediately used
- An unsupportive business model, on which the importance of an idea or a technology depends

- Alteration of the innovation process by the presence of venture capital
- The need for firms to be active sellers and buyers of IP

The definition provided by Chesbrough is also similar to what other authors have called “modular innovation” (Brusoni and Prencipe 2001), “distributed innovation” (Kogut and Meciu 2008), “dispersed innovation” (Becker 2001) which emphasise that due to an increasing dispersion of knowledge, innovative activities are distributed over a wide spectrum of heterogeneous actors.

If Chesbrough focuses his definition on the initial stages of the innovation process such as R&D (including scientific exploration and technological research) and Product/Services development, Open Innovation models may also concern and affect other stages such as Marketing and Distribution stages.

Despite the definition provided by Chesbrough, Open Innovation (OI) is not a clearly defined concept, since it considers different dimensions and can be achieved in different ways. Nevertheless, most studies identified three general distinctions: *Inbound (*also *Outside-in)*, *Outbound (*also *inside-out)* and *Coupled* OI (Dahlander and Gann 2010; Enkel, Gassmann, and Chesbrough 2009):

Outbound OI. It refers to earning revenues either with licensing or by performing another company’s activity. It is beneficial for a firm that owns internal knowledge or technologies and is searching for external organizations to commercialize it.

Inbound OI consists of acquiring external knowledge to contribute to innovation activities and is beneficial for firms that want to support innovation efforts and gain ideas and resources to exploit innovative opportunities.

Coupled OI. The coupled process refers to co-creation with (mainly) complementary partners through alliances, cooperation, and joint ventures during which give and take are crucial for success. It is a good fit for firms that want to exploit internal knowledge or technologies while acquiring external knowledge at the same time. (Pellegrino 2017)

A further distinction needs to be done in term of “*openness*”. Dahlander and Gann (Dahlander and Gann 2010) and Enkel (Enkel, Gassmann, and Chesbrough 2009) identified six main types of openness:

1. *Revealing*: revealing internal resources to the external environment without immediate financial reward
2. *Selling*: commercializing inventions and technologies through selling or licensing out resources
3. *Sourcing*: using external sources of innovation by scanning the external environment prior to initiating internal R&D
4. *Acquiring*: acquiring input to the innovation process through the market place
5. *Pooling:* it identifies the combination of revealing internal resources and sourcing external resources
6. *Jointly Commercializing:* it refers to the process of collaborating to bring an innovation to the market

Another classification of open innovation is based on the concept of **Exploration** and **Exploitation:** in the exploration stage, a firm is carrying out R&D activities to develop the innovation, whereas in the exploitation stage the firm is aiming at commercializing the innovation (Lee et al., 2010).

Several *methods of open innovation* have been identified (Pellegrino 2017) which can be categorized according to the distinctions made above. The following Table 0-5 provides an overview of these methods organized according to the distinctions of OI with a short description of each one of it and also including the type of partners typically involved in the different methods.

Type of OI	Exploration	Exploitation	Description of Methods of OI	Partners
Outbound	*Revealing*	*Selling*		
	Outsourcing	- Out-Licensing	Arrangement where a firm grants the right to another firm to use its proprietary technology	Competitors, Universities & Research Centers
		- Outsourcing	Outsourcing allows firms that do not possess the competencies or facilities to perform all the activities in the value chain to develop new innovations	Suppliers, Competitors, Universities & Research Cent.
Inbound	*Sourcing*	*Acquiring*		
	- In-Licensing	- In-Licensing	Arrangement where a firm obtains the rights to use a technology of another firm	Competitors, Universities & Research Cent.
	- Outsourcing	- Outsourcing		
	- Co-Creation		Collaboration with end users to develop a product or service	Customers
Coupled	*Pooling*	*Jointly Commercializing*		
	- Strategic Alliance	- Strategic Alliance	Voluntary cooperative agreements between firms, which can be used to access knowledge or capabilities that are not available internally	Suppliers, Competitors, Universities & Research Cent.
	- Joint Ventures	- Joint Ventures	Particular type of strategic alliance that involves equity investment from each partner and often results in establishment of a new separate entity	Suppliers, Competitors, Universities & Research Cent.
	- Cross Licensing	- Cross Licensing	The parties mutually grant each other licenses	Competitors,
	- Research organiz.		Set up cooperative research organizations such as trade associations, university-based centers or private research corporations	Competitors, Universities & Research Cent.

Table 0-5: Classification of Open Innovation (OI), various distinctions, level of openness and methods - adapted from(Pellegrino 2017; Enkel, Gassmann, and Chesbrough 2009)

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).

2.1.1 Co-opetition models

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.

The concept of coopetition emerged in 1989, proposed by Ray Noorda, president and CEO of Novell, Inc.. It draws its roots from achievements in the field of cooperative strategies, both in the single dimension (single strategic alliances) and multilateral (networks, clusters).(Cygler and Sroka 2016)

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).

Coopetitive relationships are mainly interpreted in terms of three theoretical concepts: game theory, transaction costs theory, and the resource-based approach.

In game theory, based on the classic analysis of the prisoner’s dilemma, coopetitive relationships are treated as a positive-sum game, which gives all players the opportunity to gain benefits.

Transaction costs can be *ex ante* (as the costs of negotiating process, preparation of documentation) and/or *ex-post* (adaptation costs, the cost of creating and maintaining of the management structure, execution of safeguards, coordination of activities). Among the hybrid forms of inter-organizational relations, coopetition generates the highest costs because of greater efforts in controlling and protection against loss of assets (especially intangible)(Cygler and Sroka 2016).

In the resource-based concept, enterprises decide to cooperate with organizations that have complementary and strategic resources. That may generate benefits.

Coopetitive relationships are also *created to form resources*: developing new technologies, creating or jointly acquiring information and knowledge, and acquiring significant competences(Cygler et al. 2018).

In the literature of Strategic Management, coopetition is considered having a positive impact on company performance (Garcia 2002), an increase the value of the organization; knowledge creation and transfer, innovation growth (Dagnino and Rocco 2009).

Brandenburger and Nalebuff defined the value network (*Value Net*), where five types of players: *companies*, *competitors*, *suppliers*, *customers* and *complementors* can be in coopetitive relationships (Figure 0-1).

Customers buy company’s products and services, in exchange for money. Suppliers provide resources to the company, in exchange of being paid. Competitors offer substitutes (direct or indirect) to your company's products and services. The company's competitors compete both on the customer side and on the supplier side. Complementors provide products or services that allow a customer to get more value out of the company's products or services if they buy both. Any company can act as both a supplier and competitor.

Companies are interested both in a reduction in the number of competitors and the increase in the number of the other three groups of players. Multiple horizontal and vertical relations between the value network members generate added value. The added value is greater for all players in the case of acting in the network together than would be generated as a result of independent action of individual players.

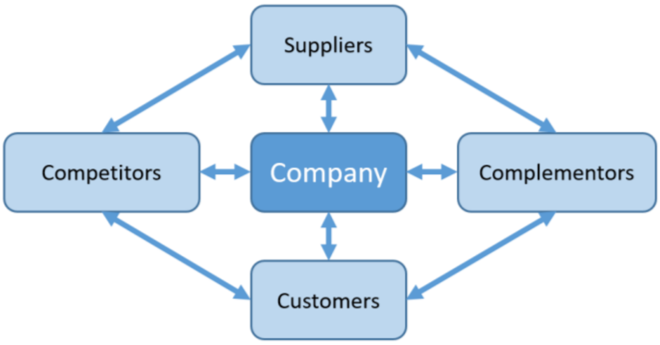


Figure 0-1: The Value Network

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. 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) (see Table 0-6) 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').

Benefits of coopetition	Risk of knowledge sharing	Mechanism for protection of knowledge
Access to competitive knowledge	Risk of knowledge spill-over	*Balance between sharing and withholding knowledge.* Protection requires classification of knowledge assets, co-opetition actors are aware of which knowledge they may and may not share with the partners
Increased competitive advantage	Risk of opportunistic behaviour of a co-opetition partner	*Intellectual property rights, contracts and agreements.* They work well in international co-opetition, less in smaller companies and local co-opetition
Faster, more efficient and novel innovation	Risk of conflict with partners	*A 'learning race'.* That is learning faster than other partners and then exit the collaboration before all partners have acquired the same knowledge from the development.

		This approach confirms the risk of knowledge sharing in co-opetition leading to opportunistic behaviour by one’s partners
Capturing of value created in the co-opetition network	Risk of lack of balance between competition and co-operation	*Complex design* Complexity of designs makes it hard for co-opetition partners to understand the design fully and, in consequence, be able to replicate it.
Synergy effects	Lack of knowledge sharing on individual level as a risk to co-operation	*Trust among the network partners*

Table 0-6 Benefits and Risks in coopetitive sharing knowledge - Extracted and adapted From (Ilvonen and Vuori 2013). Note: there is no relation among cells within a row.

1.A.6 Systems of Innovation

The most frequently quoted definition of systems of Innovation is the one of Charles Edquist (Edquist 1997): “*all important economic, social, political, organizational, and other factors that influence the development, diffusion, and use of innovations*.”

Systems of innovation are always defined as complex systems, stressing their non-linear, systemic, interactive and evolutionary character (Schrempf, Kaplan, and Schroeder 2013). According to Coenen and Lopez (Coenen and Díaz López 2010) the different SI approaches can be characterized by the following six dimensions: 1. System boundaries, 2. Actors and networks, 3. Institutions, 4. Knowledge, 5. Dynamics and 6. Policy implications. Several authors have identified different SI approaches but a consensus in their exact definition does not exist. Table 0-7 highlights definitions and consideration from different authors.

Systems of Innovation	Description
National	“*A country’s National Innovation System is a historically grown subsystem of the entire national economy consisting of organisations and institutions which play a major role in the innovative activity in the country. In the NIS approach, interactions within organisations as well as the interplay between organisations and institutions are of central importance*” (B Bozkurt et al. 2004). The development and transformation of NIS is a strategy for governments to promote competitiveness of business sector, and therefore the basis of new technology policies(OECD 2002). The NSI concept emphasizes the interaction of actors involved in innovation and analyses how these interactions are shaped by social, institutional and political factors(Schrempf, Kaplan, and Schroeder 2013)
Regional	“*Regional innovation systems may develop. The presence, for example, of local public research institutions, large dynamic firms, industry clusters, venture capital and a strong entrepreneurial environment can influence the innovative performance of regions. These create the potential for contacts with suppliers, customers, competitors and public research institutions. Infrastructure also plays an important role*”. (OECD 2002) These type of systems encourages the diffusion of knowledge, skills and best practice within a geographic area larger than a city, but smaller than a nation. (D’Allura, Galvagno, and Destri 2012; Cooke P. et Al. 2011)

Local	A spatial concentration of firms (including specialized suppliers of equipment and services and customers) and associated non-market institutions (universities, research institutes, local trade/business associations, regulatory agencies, technology transfer agencies, et.) that combine to create new products and/or services in specific lines of business.(Muscio 2006)
Technological	A dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology (spanning multiple sectors).
Sectoral	*“Sectoral system of innovation and production is a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products. A sectoral system has a knowledge base, technologies, inputs and an existing, emergent and potential demand. The agents composing the sectoral system are organizations and individuals (e.g. consumers, entrepreneurs, scientists)”* from (Malerba 2002). According to this definition, sectoral systems have the following building blocks: •knowledge base and learning processes; •basic technologies, inputs and demand, with key links and dynamic complementarities; •type and structure of interactions among firms and non-firms organizations; •institutions; •processes of generation of variety and of selection. The agents composing a sectoral system are individuals and organizations characterized by specific learning processes, competencies, beliefs, objectives, organizational structure and behaviors, interacting through processes of communication, exchange, co-operation, competition and command processes, which are shaped by institutions. Sectoral systems can undergo change and *transformation through the co-evolution* of its various elements. Innovation processes differ greatly from sector to sector in terms of development, rate of technological change, linkages and access to knowledge, as well as in terms of organisational structures and institutional factors(Malerba 2002).

Table 0-7: Systems of Innovation

From the above classification and also according to Edquist (Edquist 2001) we can identify the boundaries of SI through three approaches: 1. *Spatially/geographically,* 2. *Sectoral*, and 3. *Functionally*.

Identifying spatial boundaries of different SIs is relatively easy. Where sectorial boundaries are drawn (which can include national, regional, local) it depends on the circumstances, e.g., the technological and market requirements, the capabilities of various agents, the degree of interdependence among agents, etc(B. Carlsson, R. Stankiewicz 1991). Specific technologies or product areas define the boundaries of sectoral systems, but they must also normally be geographically delimited. The functional boundaries concern the actors which are or should be included in a SI in order to carry out certain “specific functions” or “activities” which are necessary to achieve the overall purpose (function) of a SI which has been recognized to be *to develop, diffuse and utilise innovation*. (Johnson 2011; Edquist 1997). Several authors quoted by Edquist (Edquist 2001) identify different “specific functions” or “activities” for instance: research, manufacturing, bringing together complementary knowledge, create ‘new’ knowledge, supply resources, facilitate the creation of positive external economies, facilitate the formation of markets to mention few.

1.A.7 The Impact of Innovation

A series of attributes to the innovation process have been identified which the researcher considers as describing *the impact*, the effects, which the innovation process and its outputs have on contexts different from the firms perspective which would measure impact through indicators such as *sale growth*, *customer satisfaction rating*, *market share*, etc… The attributes emerged from analysing the scientific and non-scientific literature around the topic of innovation processes utilized to present this chapter and therefore other existing attributes may exist which could not be identified by the researcher (see Table 0-8). Furthermore, through the analysis of literature, it is evident that consensus on the definition of these attributes has not been reached yet. It is however not the intent of this research to enter into such a conversation but rather to identify a specific category of attributes of the innovation process which would be discussed later on.

Innovation Impact	Description
Disruptive	A disruptive innovation ("do it differently" or "do something different") creates an entirely new market with the introduction of a novel type of product or service. It penetrates new market segments and uses technological innovations or/and new business models. Being not an intrinsic quality of the innovation itself but how the innovation acts in the market, the researcher consider more appropriate to put this attribute among the impacts rather than the "nature" of innovation as per Baregheh (Baregheh, Rowley, and Sambrook 2009). Disruptive innovation is therefore not necessarily radical and also incremental innovations can be disruptive. In their most extreme form, innovations can even change the basis of society, for example the transformations resulting from today's computing technologies (ex: block chains) (Weis 2015)
Sustainable	A sustainable innovation is a solution that has been developed to be a long –lasting, environmentally responsible solution for the provider (the business), the society and also the user (Ottosson et al. 2017)
Social	Social innovations are new ideas (products, services, models and practices) that simultaneously meet social needs and create new social relationships or collaborations. In other words, they are innovations that are both good (desirable) for society and enhance society's capacity to act (Pol and Ville 2009)
Inclusive	"*Inclusive innovation is the means by which new goods and services are developed for and/or by the billions living on the lowest incomes*" (Foster and Heeks 2013). Also defined as pro-poor innovation.

Table 0-8: Attributes describing the impact of innovation on different contexts

1.A.8 Innovation Management Techniques/Tools

A study conducted by Hidalgo and Albors for the European Commission (Hidalgo and Albors 2008) on more than 400 European companies highlights that introducing Innovation Management Techniques (IMT) can help the companies to foster competitive advantages by: Increasing flexibility and efficiency (86%), Managing knowledge effectively (76%), Improving productivity and time-to-market (73%), Improving relationships with suppliers (72%), Gathering on-line marketing information (69%), Facilitating teamwork (67%), Integrating different sources of customer information (66%), Reducing costs by using IT-based solutions (65%), Eliminating redundant processes (64%).

The study concentrated on IMTs that aim at improving competitiveness, and specifically on those IMTs that focus on knowledge as an important part of the innovation process. Below Table 0-9Table 0-9 listing IMT typologies and methods.

IMT typology	Specific methodologies and tools
Knowledge management tools	knowledge audit, knowledge mapping, document management, intellectual property rights management
Market intelligence techniques	technology watch / search, patent analysis, business intelligence, Consumer Relationship Management, geo-marketing, data mining
Cooperative and networking tools	groupware, teambuilding, supply chain management, industrial clustering, Agile, communities of practice
Human resources management techniques	teleworking, corporate intranet, online recruitment, e-learning, competence management, flat organization
Interface management approaches	research and development - marketing interface management, concurrent engineering
Creativity development techniques/Ideation approaches and techniques	brainstorming, lateral thinking, TRIZ, S.C.A.M.P.E.R method, mind mapping, Six thinking hats, Design by analogy methods (including BID), Design challenges (Ideas competitions) /Participatory design
Process improvement technique	benchmarking, workflow, business process re-engineering, Just-in-Time
Innovation project management techniques	project management, project appraisal, project portfolio management
Design and product development management tools	computer-aided design, rapid prototyping, usability approaches, quality function deployment, value analysis
Business creation tools	business simulation/virtual incubator, business plan, spin-off from research to market

Table 0-9 Typologies and methods/tools of IMT - From (Albors-Garrigos, Igartua, and Peiro 2018; European Commission - Directorate-general for Enterprise 2004; Hidalgo and Albors 2008)

B. Ideation and BID methods and tools

The review followed a cascade approach. It started from assessing general books published by academicians about Design process/Biomimicry/Biomimetics/BID, subsequent review of relevant articles mentioned in the references of the books and followed by further review of relevant references mentioned in the articles. Journals around these topics were consulted: Biomimetics, Design, Creativity, Cognitive Sciences. The same process has been followed to draft the State-of-the-art chapter.

1.B.1 Ideas generation methods and tools – an introduction

Ideation process within the Conceptual Design phase

From a design engineering perspective, it is relevant to question at which level of detail the ideation process can be deepen within the various phases of the Product Development Process. Following Pahl et al. (Pahl et al. 2007) this process can be represented as composed by four main steps:

I. Planning & Task Clarification
II. Conceptual Design
III. Embodiment Design

IV. Detail Design

In particular, the authors define the Conceptual Design phase as the part of the design process where the basic solution is identified elaborating a solution principle going through sub-phases such as:

1. identifying the essential problems,
2. establishing function structures,
3. searching for appropriate working principles and
4. combining these into a working structure

In the approach, the principles are usually not concrete enough to lead to the adoption of a definite concept. This is because the search for a solution is based on the *function structure*, and so it is aimed principally at the fulfilment of a technical function.

In particular, for the benefit of this research, the following sub-phases within the Conceptual Design phase should be highlighted:

Requirement List	This list is the result of answering questions such as: • What are the objectives that the intended solution is expected to satisfy? • What properties must it have? • What properties must it not have? It thus represents the specification against which the success of the design project can be judged. Requirements such as *Basic, Technical performance, Attractiveness* requirements. From a procedural point of view as per Pahl et al. , this list belong to the previous stage of the Produce Development process (Task Clarification) it however represents the entry point to the Conceptual Design phase
Problem Abstraction (Abstract to identify the essential problem)	In order to solve the problem of fixation and detach from conventional ideas, ignoring what is particular or incidental and emphasising what is general and essential should be pursuit. Such generalization leads to the "*crux of the task*". If the problem is properly formulated, then the overall function and the essential constraints become clear without prejudicing the choice of a particular solution in any way. Broadening the problem definition with more or less context would expand or narrow the possible space of solutions.
Establish function structure (Functional analysis/modelling)	Once the overall problem has been formulated, it is possible to indicate an overall/main function that express the solution-neutral relationship between inputs and outputs of the problem. Depending on the complexity of the problem, the resulting overall function can be more or less complex. Complexity meaning that the transparency of the relationships between inputs and outputs is relatively poor, that the required physical processes are relatively intricate, and that the number of assemblies and components involved is relatively large. So a complex or overall function can be broken down into *sub-functions* of lower complexity. The combination of individual sub-functions results in a function structure representing the overall function. The aims of breaking down complex functions are to: • determine sub-functions that facilitate the subsequent search for solutions • combine these sub-functions into a simple and unambiguous function structure. Functional analysis applied in the conceptual design phase, when only an abstract description of the product exists (so based on *what* a product must do instead of *how)*, can lead to the generation of functional variants, ad therefore expand the solutions space that designers can explore. *Physical* and *Working principles* need to be found for the various sub-functions, and these principles must eventually be combined into a working structure

Ideation methods and tools

Shah et al. (Shah, Kulkarni, and Vargas-Hernandez 2000) classify the methods for idea-generation in two main groups: *intuitive* and *logical*.

Intuitive methods are techniques which stimulate the unconscious thought processes of the human mind and so they depend on the knowledge of the user of these technique. Examples are *morphological analysis*, *checklist*, *brainstorming*, *SCAMPER*, *6-3-5 method*, *Gallery method*, *C-sketch*, *mind maps*, *fishbone diagram* to mention some (Chulvi et al. 2013).

Instead logical methods involve systematic decomposition and analysis of the problem and therefore depend on physical principles, catalogues and databases. Examples of logical ideation methods are *physical effects*, *working principles, artifacts catalogs*, *design-by-analogy methods* (which includes BID), *Design repository* relating functions to artifacts. Certain techniques are considered *mixed* such as *TRIZ*, *Morphological charts* and *Factorization methods*. (Mohan et al. 2014).

Also Moreno et al. (Moreno et al. 2015) provide an overview of ideation methods but with a different categorization between *intrinsic* - where ideas are triggered from intuition or previous experience - *extrinsic* -that make use of heuristics, prompts or with stimulus/assistance external to the designer - and mixed ones.

Different cognitive mechanisms, called *ideation strategies* or *components*, have been identified that are believed to intrinsically promote creativity and ideation and help designers the remove mental blocks such as design fixations.

Evaluating specific ideation methods in their entirety is complicated because these ideation components can operate simultaneously (Hernandez, Shah, and Smith 2010). Some of the components identified are: *Provocative Stimuli*, *Suspended Judgment*, *Flexible Representation*, *Frame of Reference Shifting*, *Incubation*, *Example Exposure*, *Abstract the problem* among others (Shah, Smith, and Vargas-Hernandez 2003; Mohan 2011) Table 0-10.

Ideation Strategies	**Description**	**Mental blocks that can be removed**
Suspend judgment	A designer can suspend his judgment by not prematurely taking a decision about his ideas. This is done by reducing the character of being judgmental. By suspending judgment, the designer would not lose any of his past ideas and he won't reject any alternatives which might be helpful in future.	Pre-mature judgment, Unable to find fundamentally different ideas
Emphasize quantity	By emphasizing quantity of ideas more, no ideas will be rejected at the early stage of idea generation thereby helping the designer in having a large number of design alternatives at the end of ideation process since not much emphasize would be given for novelty and quality.	Pre-mature judgment
Shift frame of reference	A designer might focus only on a particular area and he might generate same kind of ideas again and again. This is because, the ideation space of the designer is very narrow and he is not exploring the design space. In order to explore and expand his design space, he can change his frame of reference so that he can explore unseen areas and find a totally different idea from his previous ones.	Unable to find fundamentally different ideas, Bias towards past design, Tight grip on technical requirements
Use of analogies and metaphors	Analogies and metaphors are supposed to fuel up a person's creativity. Analogies from another field will help in coming up with new inventive designs (stimulating *lateral thinking*). Cognitive studies confirm that more analogies lead to a better analogical transfer. Biologically-Inspired Design approach focus specifically on this ideation strategy	Tight grip on technical Requirements, Design fixation, Bias towards past design

Apply provocative stimuli	Provocative stimuli can be provided by things around a person, namely pictures, sounds or videos. Stimuli can also come from another designer's idea. Giving a stimulus to a designer helps him to overcome fixation when he is not able to generate any useful ideas.	Design fixation, Bias towards past design
Making random connections	Random connections between different concepts and solution principles can be used to get a novel and different concept which has features from all the individual concepts.	Design fixation
Incubation	When a designer is fixated (mental saturation or tired), he can take a break i.e. staying away from problem for some time. By doing this, he allows his subconscious mind to think about the problem while he is taking a break.	Design fixation
Breaking rules/ suspending constraints	By having constraints, a designer restricts himself to a very narrow design space. Breaking these rules and constraints helps him to expand and explore the design space and come up with different solution which might be novel (since he suspended his constraints and considered the problem to be very abstract).	Conflicting requirements that appear to be physically Impossible, Fictitious constraints
Abstraction of problem	A problem can be abstracted by using different words to describe the problem thereby removing constraints that were initially imposed. Using of common/abstract words makes a designer think in a different perspective.	Conflicting requirements that appear to be physically impossible
Using sketches/ graphical representation	As we know, pictures are worth a thousand words. When pictures or sketches are used, it conveys the ideas more easily and there is much scope for improvement. A lot of functional features can be explained in a picture easily which might be difficult to represent by text.	Rigid problem representation
Example exposure	Related examples can be provided to a designer to easily come up with a solution from the stimulus given by an example. Examples are an integral part of many ideation methods. Of course, since the ideas are based 20	Lack of domain expertise
Imposing/Removing fictitious constraints	During a design process, some constraints are imposed with or without a designer's knowledge which reduces his design space. These constraints might be applied by the designer to improve the functional quality of the design but it might actually hinder him from thinking in a divergent manner thereby making him generate less novel ideas.	Fictitious constraints

Table 0-10: Ideation Strategies - Adapted From (Mohan 2011)

1.B.2 Design by Analogy

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. Analogical association and retrieval in human cognition depend on how a problem is represented, where previous research shows that multiple representations facilitate analogical reasoning through the retrieval of effective and novel analogies stored in designers' long-term memory. (Moreno et al. 2014) (J. S. Linsey et al. 2007) (Chakrabarti et al. 2011)

Design-by-Analogy (DbA) has shown effectiveness in generating novel and high quality ideas, as well as reducing design fixation (Moreno et al. 2015) and can be therefore effective at forstering creativity and innovation.

Several DbA methods have been developed. Their sources of analogies vary from:

- answering direct questions that allow exploration of analogical categories, as in Synectics (Gordon, 1961),
- taking inspiration from the natural world (French 1998),
- developing biomimetic and bioinspired concepts (e.g.: Chiu and Shu 2007; Chakrabarti et al. 2017; Nagel, Nagel, and Stone 2011; Vattam et al., n.d.),
- developing analogous solutions from abstractions of functional models and flows (e.g.: Mcadams and Wood 2000),
- generating sources of analogous domains by means of design problem re-representation and semantic mappings (e.g.: Linsey, Markman, and Wood 2008) and
- using analogical search approaches and search engines to identify potential analogies from digital sources, databases and repositories (Vandevenne et al. 2015; 2011).

The most prolific ones, and object of this research are the bio-inspired concept which can be categorized under the term Biologically-Inspired Design (BID) methods and tools.

1.B.3 Biologically-Inspired Design methods and tools

Analogical reasoning

The potential of BID methods lay 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). *Cross-domain* analogies yielded more original ideas than *within-domain* analogies, which yielded more ideas in quantity (Jin and Benami 2002).

Furthermore biological solutions, following principles different from technological solutions such as multi-functionality and being eco-system oriented could allow the designers to access different and unusual solutions providing the opportunity to get rid of design fixations and be exposed to new and efficient design strategies. Thus, biomimicry, both extending the scope of solutions to distant solutions and providing solutions based on a different principles, it has therefore potential to generate ideas which could turn into innovation.

According to Vincent (Vincent 2001) the knowledge transfer between Biology and Engineering can be executed at different levels of abstraction (Figure 0-2).

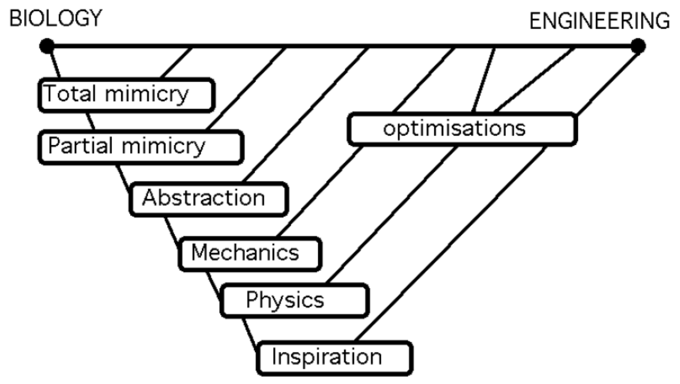


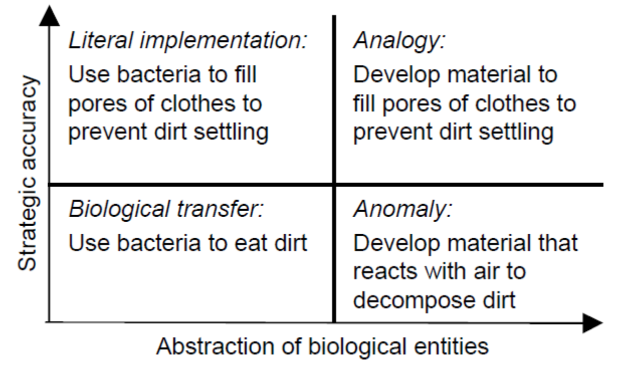
Figure 0-2: Biomimetic map – Vincent 2001

A biomimetic "map" to illustrate the idea that the more abstract a concept is, the more adaptable it is within another discipline (Vincent 2001). The general concept, however not explained in detail by the author, is that the further down one can move from the natural origin (top left) the more general the concept of bio-inspiration will be and it will lead to different solutions and/or different levels of improvement on the final design.

Mak and Shu (Mak and Shu 2008; 2004) assess the processes involved with the selection and use of relevant biological phenomena (forms, behaviours and principles), and the quality of resulting analogies evoked. They identified the following types of similarity relationships between the concepts generated and the biological phenomena utilized:

- *Literal implementation*. The first type of similarity relationship is characterized by literal implementations of biological forms and behaviours. Biological forms carry out a strategy found in the biological phenomenon, but in an engineering context, e.g., use cockleburs directly for adhesion.
- *Biological transfer*. Biological transfers fixate on biological forms, but use strategies inconsistent with those found in the biological phenomenon, e.g., use cockleburs as button fasteners.
- *Analogy*. Analogies implement strategies found in the biological phenomenon without transferring the biological forms, e.g., use the idea of many small hooks for adhesion. In this case, the concept is based on deep relational similarities. This category represents the type of similarity intended in biomimetic design.
- *Anomaly*. An anomaly does not involve any apparent similarity between the concept and the biological phenomenon on which the concept is based.(Mak and Shu 2008; 2004)

To map the relationships between concepts developed and biological phenomena utilized, they used the axes of *accuracy of the strategy applied* and *abstraction away from biological entities*. Resulting types of similarities are shown in Figure 0-3**Error! Reference source not found.**.



Literal implementation: Use bacteria to fill pores of clothes to prevent dirt settling

Analogy: Develop material to fill pores of clothes to prevent dirt settling

Biological transfer: Use bacteria to eat dirt

Anomaly: Develop material that reacts with air to decompose dirt

Figure 0-3: Types of similarity relationship between the concepts generated and the biological phenomena utilized referring to the specific experiment conducted in (Mak and Shu 2004). The problem was to develop alternative concepts that will result in clean clothes substituting harmful dry cleaning solvents.

BID process

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)

The process to carry out these approaches can be split into specific steps and different authors tend to use more or less steps or giving the steps different definition. Fayemi (Fayemi et al. 2017) offer a review of most known BID methods aligning their stepped problem-driven process with another one as reference process by (Massey and Wallace 1996)

In this research a six steps problem-driven process and seven steps solution-driven process are considered as per (Helms, Vattam, and Goel 2009) with additional considerations when considered necessary (Table 0-11Table 0-11, Table 0-12):

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 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 2009). 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. Some authors refere 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. 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 (Abstraction)	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 2009) 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/Idea generation	After the principle is extracted from the biological solution, designers translates the principle into the new domain. This translation involved 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 2009) Design concepts can be generated. This activity will culminate in the embodiment of a bio-inspired solution of a technological product or system. 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 0-11: 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 than 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 0-12: Steps of the Solution-driven approach

Functional analysis and Functional modelling of biological systems

In engineering design, all products and artifacts have some intended reason behind their existence: the product or artifact function. Pahl et al. provide a definition of function as *an action being carried out on a flow to transform it from an input state to a desired output state*, were *flow* refers to the type of material, signal or energy that travels through a system or a device. With this definition, function refers more to a *verb* and flow to the *object* of the function. A functional model as defined by Hirtz et al. is an Abstract conceptualization of an artifact, product or system in terms of its functions (Hirtz et al. 2002).

Functional analysis (or modelling or decomposition) provides a method for understanding and representing an overall product or artefact function. A Functional model is a "description of a product or process in terms of the elementary functions that are required to achieve its overall function or purpose" (Stone and Wood 2000). During this process, the overall function of the system is decomposed by smaller sub-functions in order to transform the system main function to alternative sub-functions that can be easily addressed by designers. This modelling process explains the system architecture, structure and behavior.

It can guides design activities such as: problem decomposition, ideas/concepts generation (through a sort of design-by-analogy process) and also to assist in the abstraction of biological systems in BID (Vakili et al. 2007; J. K. S. Nagel, Nagel, and Stone 2011; R. L. Nagel et al. 2008; Vattam et al., n.d.; Stroble et al. 2009).

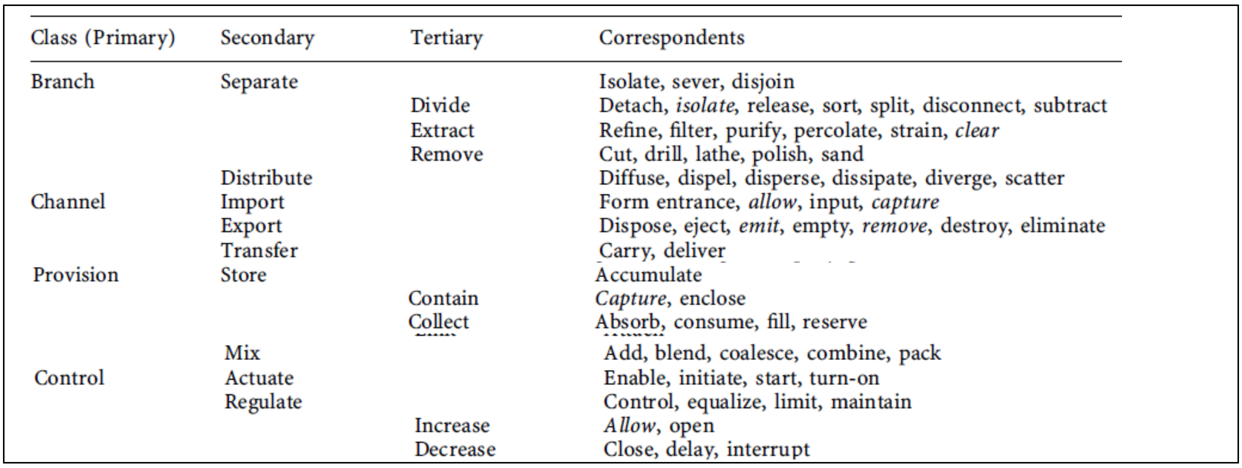
To support functional modelling processes, there have been several attempts to define a functional ontology, to formalize function representation via standardized set of function-related terminology which could lead to repeatable and meaningful results from such a representation. These representations are defined as "*functional basis*".

The most quoted in literature is the *NIST Functional Basis (FB)* which was generated via an extensive review of the literature yielding a large body of function- and flow-based terminology within the context of engineering function. Lists of functions and flows were then distilled into smaller ones removing synonyms, eliminating functions that were specializations of more generic functions, and by eliminating flows that were specializations of more generic types of flows. The lists of functions and flows were then categorized hierarchically and organized into taxonomies. The taxonomies developed at NIST contain over 130 functions and over 100 flows. (Hirtz et al. 2002)
Several authors developed functional basis for engineering design when other even to assist the retrieval of biological knowledge for bio-inspired design (ex: the Biomimicry functional *taxonomy* of Asknature.org). Attempts have been made also to combine engineering and biological functional basis with the attempt to improve the BID process such as an engineering-to-biology thesaurus(Stroble et al. 2009) and the combination of the NIST FB with the Biomimicry Taxonomy(Baldussu and Cascini 2015).
Utilizing the NIST FB (Hirtz et al. 2002), Fantoni et al. (Fantoni, Taviani, and Santoro 2007) proposed a lexical-analysis-based approach to function based design investigating synonyms and antonyms. This investigation should lead to the development of functional variants in a sort of design by analogy process. If new solutions could arise investigating similar functional concepts by using synonyms, on the other hand, antonyms, allowing designers to switch from a function to its opposite, could increase the effectiveness of lateral and diverging brainstorming approaches (Fantoni, Taviani, and Santoro 2007).

One element which seems common to all the functional basis is that functions are grouped hierarchically, with a top-down structure, from a *primary* level (class) to *secondary*, *tertiary* and *correspondents* level, as in NIST and reconciled version (with a total of 130 functions and sub-functions considered), and from *group* (8), *sub-group* (30) and *functions* (62) in the Biomimicry Taxonomy.

Why hierarchies? The hierarchical structure seems having derived from a practical operative reason. In the words of Szykman et al. "*It is important to note that the categorizations used in the taxonomies are not unique, but are rather a matter of convenience…However, an alternative categorization could have organized them by the mapping of variable types across domains. The importance should be placed on the content of the taxonomy rather than the specific approach to organizing the terms….The need for standardized terminology in function-based design is often overlooked in the literature; however, it is an issue of critical importance for a number of reasons. The first reason is to reduce ambiguity at the modeling level.* ***Ambiguities*** *can occur when multiple terms are used to mean the same things, or when the same term is used with multiple meanings. The distillation of a large body of terms into concise taxonomies does not eliminate this problem entirely, but it significantly lessens its occurrence…*[The second reason]..*The larger the number of terms there are in a vocabulary, the more different ways there are to model or describe a given concept. This makes processing of information that has been represented more difficult, whether it be a human trying to interpret information modeled by somebody else, or whether it be algorithms developed for function-based reasoning or design automation….In practice, it is impossible to have a vocabulary that allows all concepts to be modeled, in only one unique way, because it is the flexibility required for representation of a broad set of concepts that results in multiple ways of expressing the same concept… A third reason for developing a standardized terminology is that it increases the uniformity of information within function models. This will facilitate the exchange of function information among distributed researchers and developers, and will greatly simplify the task of indexing and retrieval of information for the purposes of function-based searches and query capabilities.*"(Szykman, Racz, and Sriram 1999).

A further element to be highlighted in the reconciled functional basis is the presence of italicized words which are repeated *correspondents (*Figure 0-4*)*. For example, "*capture"* or "*allow*" are both correspondents for the secondary functions as well as respectively for the tertiary functions "contain" and "increase".



Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Mix		Add, blend, coalesce, combine, pack
Control	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt

Figure 0-4 Extracted from the Reconciled Functional Basis highlighting repetitions of functions

Repetitions, to a much lesser extent, appear also in the engineering-to-biology thesaurus of Stroble where correspondents such as “blood”, body” and “lipids” are repeated in different classes.

If ambiguities occur in the domain of engineering, similar ones occur in the domain of biology when describing the function of a living system or its components. Moreover, in biology it seems no attempt has been made to generate a biological functional basis. This amplification of ambiguities deriving from different use of similar words and different meanings of the same word is increasing the difficulty in finding operative bridges between engineering and biology in the practice of BID.
On the basis of the above issues, the researcher argues that, especially when trying to integrate engineering and biology domains for BID purpose, a hierarchical/taxonomically organization of functions may not be the most effective way of organizing functions.

The taxonomy are fixed and do not allow evolving, a network structure would allow to add connections among functions.
Repetitions such as these ones in both engineering and biology domains functional models may suggest that a systemic/networked structure of the functional basis could be more appropriate, at least from a theoretical perspective, than a hierarchical one. Especially in the practice of BID where functions in biology language may have different synonymous and a highly contextualized meaning.
Fantoni et al.,(Fantoni, Taviani, and Santoro 2007) in their approach somehow delink from the hierarchical structure.

The Biomimicry Taxonomy (https://asknature.org/resource/biomimicry-taxonomy/) has been developed by the Biomimicry 3.8 and it is the structure upon which biological solutions (1728, up to march 2020) are organized in Asknature. It is a taxonomy of natural functions subdivided in three levels:

- Function Groups (8)
- Sub-groups (30)
- Functions (162)

The eight function groups are the following:

- Break down (86 entries)
- Get, store, or distribute resources (400)
- Maintain community (192)
- Make (127)
- Modify (371)
- Move or stay put (296)
- Process information (263)
- Protect from physical harm (776)

The Taxonomy has been developed by Biologists, utilizing biological language and meanings. Also the biological solutions included in Asknature are extracted from biological literature. Therefore the search in Asknature by keywords requires already a certain level of biological knowledge to individuate the correct keyword to perform the query. Also using functions as keywords may not necessarily provide all the potential biological solutions a BID process could exploit as direct correlation between technical and biological function is not certain.

In order to solve this problem, Baldussu (Baldussu 2014) proposes a correlation matrix between the Biomimicry Taxonomy (developed by biologists) and the NIST Functional Basis (developed by designers). Thanks to the use of the Correlation Matrix, it is possible to browse Asknature in a not standard way, individuating the correct classes of biological function correspondent to the functional problem under analysis in order to browse the database by functional categories.

According to the researcher, if this approach can bridge the two domains (biology and engineering/design) it has to be highlighted that merging two functional taxonomies conceived separately by two different domains, it may not guarantee that potential solution spaces are left un-explored. Reframing a functional taxonomy where both biologists and designers works together agreeing on terms and meanings may allow accessing larger and more effective solution spaces.

Koaki and Mizoguchi (Kozaki and Mizoguchi 2014) also developed an Ontology Explorer for Biomimetics databases. It is based on linked data techniques and allows the users to find important keywords so that they can search meaningful biological knowledge from various databases. Exploration of an ontology can be performed by choosing arbitrary concepts from which *multi-perspective conceptual chains* can be traced, according to the explorer's intention.

Unfortunately the researcher could not find more relevant information on this approach to assess it.

More relevant BID methods and tools

For a broader picture on BID methods and tools, Wanieck et al. (Wanieck et al. 2017) made a recent review, which identified 43 BID tools. The methods have been conceived from 1987 onward.

The authors identified that the majority of the analysed tools serve as transfer (33%) and identification of biological models (37%) tools, while selection of biological models (12%) and abstraction (18%) tools are less represented. No tools were identified which facilitate the solution-driven approach only and in most cases, it was not specifically indicated by the developers whether the tools were developed for the solution-based. Furthermore the authors differentiated the tools according to types:

- *Database/static list/catalogue* (DSC): a collection of biological organisms, biological characteristics, biological construction principles, biological functions or the like. This list changes or evolves only if updated.
- *Taxonomy*: an orderly scientific classification categorising certain principles.
- *Thesaurus*: it aims at facilitating cross-domain communication (engineers-biologists). They function as a type of dictionary, translating biological terms into their technological equivalents and/or vice versa.
- *Ontology*: It aims at categorizing biological principles and abstract the diverse phenomena of biology into descriptive functions.
- *Algorithm*: an automated procedure for solving a certain task in a finite number of steps. In the context of the study, tools were classified as algorithms if they describe a set of steps which help to complete a task of the biomimetic process. Not necessarily software-based.
- *Method*: it describes a way of doing a task during the BID process.

Among these BID tools, the most frequently mentioned and tested in scientific literature are briefly described in Table 0-13.

BID methods/tools	Description
BID Methods/Tools without Databases	

Function-based, biologically inspired concept generation (R. L. Nagel et al. 2008; J. K. S. Nagel, Nagel, and Stone 2011)(Nagel et al., 2010)	The generation of functional models of biological systems is expected to enhance innovation and provide designers with better understanding of the design problem in general and of the functional mechanisms in particular. Nagel et al. devised an approach that uses functional modeling and the Functional Basis to capture, in one form, the biological world in design. The biological knowledge have been retrieved from Life Science Text Books and not specialized biological papers.
Engineering-to-biology thesaurus (Stroble et al. 2009; J. K. S. Nagel, Stone, and McAdams 2010)	The engineering-to-biology thesaurus provides direction when choosing the best-suited function or flow term to objectively model a biological system. A wide range of biological terms have been collected and placed into the thesaurus, which can accommodate a designer when developing functional models of well known to just introduced biological systems. The biological knowledge have been retrieved from Life Science Text Books and not specialized biological papers.
Natural-language approach (Chiu and Shu 2007; Cheong and Shu 2013)	The basic approach of this method concerns the matching of Functional Basis terms with meaningful biological keywords. The keywords used in the search strategy are cross-referenced with *Wordnet* to define a set of natural-language keywords for yielding better results during the search. Typically, searches are based on multiple keywords. Later in 2008, Cheong *et al.* used the search strategy in conjunction with the terms of the Functional Basis to identify biologically meaningful words. The Functional Basis functions in the secondary, tertiary and correspondent levels were analysed to develop groups of words that were similar according to WordNet. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically significant and connotative function keywords.(Fu et al. 2014)
BID Methods coupled with Database	
Biomimimcry Thinking/ Asknature (Baumeister and et Al. 2011) https://asknature.org/	This methodology includes an integral repository and online system known as Asknature and two main tools: the Biomimicry Thinking "wheel" and the Life Principles. The wheel represents the different steps of the BID process and the Life Principles are a collection of overarching principles identified recurrently in nature that can be utilized to give specific constraint to the abstracted problem or to evaluate the solutions vis-à-vis natural principles of sustainability (ex: adapt to local conditions, optimize use of energy and matter, multi-functionality, etc..). Trained biologists were responsible for gathering and generating the entries of biological data on Asknature. Information comes from scientific journals and books and perused scientific news, looking for leads on functional biology that might be of interest to innovators working to solve human challenges. Strategies were selected subjectively based on the researchers' assessment of whether the strategy held some potential for being useful within the field of bioinspired design. Following the selection of strategies they have been clustered and classified in the so called Biomimicry Taxonomy, which categorizes strategies according to three levels: groups (highest level), subgroups, and function. Overall, the taxonomy includes 8 groups, 30 subgroups, and 162 functions. (Deldin JM. and Schuknecht M. 2014).
SBF Modelling and the **DANE** - Design by Analogy to Nature Engine Interactive Computational Tool (Goel, Rugaber, and Vattam 2009) http://dilab.cc.gatech.edu/dane/	DANE (Design by Analogy to Nature Engine) provides a framework and access to a design case library containing Structure-Behavior-Function (SBF) models of biological and engineering systems. It also allows the designer to conceive SBF models of new systems and enter them into the library. Based on the information provided in DANE, users may search and access systems through a functional representation embedded in the library. Search results are presented to users in various multi-media forms. Note that in SBF analysis, functions are mental abstractions chosen by the modeller, and not intrinsic to the complex system. The biological models current available in DANE (22)
SAPPhIRE model and **Idea-Inspire** database	The software package *Idea-Inspire* allows one to search a database with a function-behavior-structure set, which is a verb-noun-adjective set. The database is comprised

(Chakrabarti et al. 2017; Chakrabarti et al. 2005)	of natural and artificial complex mechanical systems. Each entry's motion or process is described in the form of a function-behavior-structure model. When using Idea-Inspire, the user abstracts a desired solution action by choosing terms that describe the function, behavior and structure from a pre-defined list of terms. The Idea-Inspire software yields seven behavioral constructs following the SAPPhIRE model – state change, action, parts, phenomenon, input, organ, and effect – for each search result that adequately fit the chosen function-behavior-structure set. SAPPhIRE explains the causality of natural and engineered systems. The aim of the software is to inspire ideas rather than solve the problem directly.
BioTRIZ Database (Vincent and Mann 2002; Vincent et al. 2006; Bogatyrev and Bogatyreva 2009)	This particular approach seeks to connect biomimetics systematically with TRIZ by redefining the 39 generalized parameters and contradiction matrix of TRIZ into a simplified BioTRIZ matrix of 6x6 fields of principles. Through this approach, operations appropriate to biomimetics and bio-inspired analogies are mapped directly to TRIZ principles. The matrix was developed analysing some 500 biological phenomena, covering over 270 functions, at least three times each at different levels of hierarchy. In total, about 2500 conflicts and their resolutions in biology were identified, sorted by levels of complexity.
Find-Structure (Helfman Cohen, Reich, and Greenberg 2014b)	The database of Find-Structure (http://findstructure.org/) 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.

Table 0-13 Most frequently researched BID methods and tools divided in two categories: assisted or not assisted by specific databases repositories of biological knowledge.

Attempts have also been made in combining methods to produce more effective BID such as the UNO-BID Unified ontology for causal-function modelling in biologically inspired design (Rosa, Cascini, and Baldussu 2015).

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