UNO-BID: unified ontology for causal-function modeling in biologically inspired design

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(*Received 18 October 2013; accepted 2 July 2014*)

1. Introduction

Using Nature as a source of inspiration for solving problems is not a recent idea: since their first day on Earth, Humans have searched in Nature answers for their practical needs (French, 1994). This generic and simple idea evolved along with mankind needs and capacities (Bar-Cohen, 2006; Vogel & Davis, 2000), to become a bio-inspired design (BID), a design method that relies on Nature as a source of inspiration for inventive design tasks and for solving complex engineering problems. This approach to problems is constantly gaining popularity and consensus among the scientific community (Bonser & Vincent, 2007).

Many of the several reasons of this trend have their rationale in the belief that bio-inspired products and processes will exhibit higher performances and reduced environmental impact since, over the last 3.8 billion years, Nature has gone through a process of trial and error to refine the living organisms, processes, and materials on Earth. According to the Darwinian vision of evolution (Vincent, 2002), the biological systems that survived such a process are likely to be very resistant, energy efficient, and well integrated with the environment (Vincent, 2002). Nevertheless, biological systems are still marginally used as a reference for triggering the generation of inventive solutions and to learn from such a long experience. The lack of systematic and efficient means for

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supplying to designers and engineers the information about the lessons learned from Nature is certainly one of the main obstacles to the exploitation of such incredibly reached knowledge base.

In the past decades, several scientists endeavored to study and develop biomimetic solutions both for industrial and scientific purposes; nevertheless, only recently, systematic investigations of the BID approach emerged.

Even though several BID models appeared in engineering design literature during the last decade, none of them has still been adopted as a basis for the development of further design tools and methods.

Among the others, two main frameworks have received regular improvements and extensions by their developers, namely the SAPPhIRE model by Chakrabarti, Sarkar, Leelavathamma, and Nataraju (2005) and the Design by Analogy to Nature Engine (DANE) model by Goel, Vattam, Wiltgen, and Helms (2012) and Vattam, Wiltgen, Helms, Goel, and Yen (2010) (more detailed references are provided in the next section). Both are characterized by interesting insights and some practical examples have demonstrated their potential applications and benefits. Nevertheless, they present complementary features that would deserve a richer dialectical discussion.

DANE's library of structure–behavior–function (SBF) models of biological systems contained, in 2010, about 40 SBF models, including 22 models of biological systems and subsystems (Vattam, Wiltgen, et al., 2010). Similarly, in the same period, 20 biomimetic examples were collected and modeled with the SAPPhIRE model of causality (Sartori, Pal, & Chakrabarti, 2010).

Looking at the number of collected examples, it is possible to draw the conclusion that one of the bottlenecks in the practical use of these models is related to the population of the database of examples. In fact, the understanding of a natural phenomenon described in biological terms is an extremely time-consuming task for the designers. In order to move toward computer-aided systems that automatically compile the database of Nature's solutions, it is fundamental to conceive a model capable to represent the widest variety of natural phenomena.

This paper aimed at contributing to this debate with the ultimate goal to bring some suggestions for the construction of a reference model for BID.

The above-introduced lack of a reference model can be faced by pursuing three different alternative strategies: (i) the proposal of a novel model, based on the lessons learned from the existing models, but redefined from scratch; (ii) the selection of the fittest among the existing models and its improvement by adding the missing features; and (iii) the integration of the existing BID models to gain from the synergic effect of their hybridization.

Despite its intrinsic higher complexity, the authors opted for the latter approach, because it is expected to better exploit the past experiences and because it has the highest chances of acceptance by the scientific community.

According to this objective, the specific research question addressed by this paper is to check the compatibility between the selected BID models with the perspective of proposing an ontology compatible with these models, and also capable to overcome their limitations and fully exploit their potential.

Besides this research interest, the analyses presented hereafter are also aimed at contributing to a deeper and clearer understanding of the ontologies of the two selected models. This knowledge can help BID designers and engineers to select which model is more appropriate for their needs and to ease their efforts in understanding what each element of the models represents.

Therefore, Section 2 surveys the most commonly diffused modeling techniques within the BID scientific community and introduces the main characteristics of SAPPhIRE and DANE. In Section 3, these models are examined and discussed in more detail through two practical examples, with the aim of showing their structures, peculiarities, and limits. In Section 4, the methodological approach for SAPPhIRE and DANE ontological analysis is first introduced and then applied, so as to build an integrated ontology for BID in Section 5. This section details the most relevant outcomes of this study. In the last section, the findings described in the previous one are briefly summarized. A constructive discussion about the planned further developments concludes the paper.

2. An overview of systematic approaches for BID

This section presents a general overview of BID approaches and highlights the most recent research lines in the field. SBF and causal models will be analyzed in detail, in order to introduce a possible evolution of the natural systems representation techniques currently adopted within BID.

2.1 General overview

The term bionics, the former name of biomimetic, was coined in 1958 by Jack Steele (US Air Force) to define the science of imitation of natural systems with technical artifacts. Since then, the growth of this science steadily continued and it is now widespread in many engineering fields (e.g., materials, mechanics, and robotics). In the last decade, a novel thread appeared in this field: BID, *an approach to design that espouses the adaptation of a function and mechanism in biological sciences to solve engineering design problems* (Vattam, Helms, & Goel, 2010). The prominence of the design perspective in this definition denotes the shifting from the development of a single product based on a biological system, toward the development of a universally applicable systematic approach. In BID approaches, in general, it is possible to identify two main activities.

First, the designer is called to identify the biological systems that can help to conceive innovative and advantageous technical solutions; in this first phase, the designer has to face the cultural gap between engineering and biological scientific knowledge. Secondly, the designer has to transpose the underlying principle from the biological to the technical domain. The first task is usually problematic for engineers, mainly because of their lack of knowledge in the biological field, while their technical knowledge is usually sufficient to technically implement the natural principle.

Another important obstacle consists in the "organization" of the biological knowledge, typically unrelated to the traditional engineering design needs.

Several strategies have been developed to overcome these obstacles, see also Goel, McAdams, and Stone (2014) and Chakrabarti and Shu (2010).

A first cluster of approaches is based on the idea that it is possible to directly and automatically extract from biological literature all the BID relevant information. In other words, these methods are based on the definition of a network of connections between *Engineering Functional Keywords* and *Biological Terms*. The key search is therefore based on search engines capable to analyze books written in common language (English, for example) (Ke, Wallace, & Shu, 2009; Shu, Ueda, Chiu, & Cheong, 2011). Actually, this approach is usually employed in combination with other methods, in order to ease the solution search step (Parvan, Miedl, & Lindemann, 2012).

The key idea of the second group of approaches consists in a preliminary translation of the biological knowledge into a language and organization suitable for engineers.

This translation does not need to be exhaustive or highly detailed, since a biologically inspired technical system is not supposed to mimic a natural system in strict terms. In fact, the knowledge of the core principles of the natural system (behavior and/or structure, as explained below) is usually sufficient to properly direct engineers in the preliminary design phases. In most cases, these methods rely on a searchable archive of biological solutions described under an engineering perspective. Bio-TRIZ and Biomimicry Database (AskNature) are two noteworthy examples of this category of approaches. Bio-TRIZ is a peculiar evolution of the classical TRIZ method. It was developed by Vincent and Mann (2002) using biological phenomena (instead of patents) as a basis; Vincent's research has also been aimed at defining a "biological" matrix of contradictions (i.e., a matrix each cell of which points to the principles that are most frequently used in living organisms to resolve contradictions) and to apply it in the technical domain. The databases of biological solutions available and freely accessible online are another family of results of this approach (www.asknature.org and www.bionics2space.com). AskNature maybe the most acknowledged one. One of the typical difficulties designers encounter while using these general-purpose databases consists in the definition of appropriate search criterions through biological terms.

The research presented in this paper is mainly focused on a third group of strategies, based on high-level descriptive models of biological systems. The common aim of these models consists in representing biological systems, avoiding excessive biological technicalities, in order to make these representations accessible also to people with no biological knowledge. Designers can therefore more easily find out the fundamental principles of a biological system and then embody these natural principles in the technical field. Among these models, the SBF modeling language used in the DANE software and SAPPhIRE implemented in the IDEA-Inspire software (IDeaS Lab – Centre for Product Design and Manufacturing Indian Institute of Science, n.d.) certainly are the most widespread ones. The resulting models can then be indexed in order to ease designers search task. The definition of the basis used to index the solutions is of extreme importance, because a misleading search criterion or an incomplete correlation between biological solutions and their possible technical applications can greatly limit the efficacy of these approaches. The approaches categorized in the first group can greatly help in reducing this risk (Cheong, Chiu, Shu, Stone, & McAdams, 2011; Cheong, Shu, Stone, & Mcadams, 2008).

In turn, the models of the latter group are representations used to aid engineers in understanding biological systems, and in transferring this knowledge into engineering applications. These models are described in Sections 2.2–2.4.

2.2 Functional models

With the aim of easing the adaptation of Nature's solutions to engineering contexts (Nagel, Nagel, Stone, & McAdams, 2010) proposed a method to represent biological systems by means of functional representation (Pahl, Beitz, Feldhusen, & Grote, 2007) and abstraction techniques. They adopted an "engineering-to-biology thesaurus (Nagel et al., 2010) that maps biological terms to the functional basis" "to assist with terminological differences and to facilitate biological functional modeling."

The approach followed by Rosa, Rovida, Viganò, and Razzetti (2011) can also be included in this category. They developed an archive of biological solutions, indexed on a functional basis (i.e., according to the NIST functional basis (Hirtz, Stone, Mcadams, Szykman, & Wood, 2002)). A first peculiarity of this approach is the widening of function definition to embed environmental information directly in the definition of the function, so as to focus on solutions that are likely to be embeddable in a specific engineering context. Another peculiarity of this archive is the availability of free-text fields to summarize structure and behavior of the biological solutions, and hence the integration of informal textual annotations suitable for a "social" enrichment of the information base.

2.3 SBF models in BID: DANE

While functional models are mainly focused on device input and output, the SBF models put emphasis on the representation of the internal processes, the consequence of which are device output states (see, e.g., Bhatta & Goel, 1994).

Among the systems explicitly based on the SBF framework, DANE is probably the most acknowledged in the BID community.

According to Vattam et al. (2011), the origin of this SBF model lies on the functional representation (FR) schema (Bhatta & Goel, 1994; Chandrasekaran, 1994). Even if this model was conceived to represent the Structure, Behavior, and Function, the causality of relations is not ignored. In the FR schema, "how the device achieves the function is given by a causal process description (CPD)," that, according to Chandrasekaran, "can be thought of as a directed graph whose nodes are predicates about the states of the device, and links indicate causal transitions."

Goel and his research group continuously evolved the SBF model (Goel, Rugaber, & Vattam, 2008) and finally applied it in the BID field (Vattam, Wiltgen, et al., 2010). The more tangible result is an interactive tool for supporting BID called DANE that was conceived to provide "access to a design case library containing Structure–Behavior–Function (SBF) models of biological and engineering systems" (Vattam, Wiltgen, et al., 2010).

In this model, the function is represented by means of a schema that specifies "initial" and "final" conditions of the system, with the aim of representing what the system actually does. The function is accomplished through a progression of states through which the system evolves, each described by a set of physical variables defining the relevant properties of the system. The behavior consists of this sequence of states, together with the causal explanation of the transition between them (Design & Intelligence Laboratory – Georgia Tech, 2011). Usually, these explanations consist in a physical phenomenon or principle that governs the state transition. Finally, the structure is represented by means of a box diagram. Figure 1 shows an example.

The formal definitions of the main components of their model can be found in a previous paper (Goel et al., 2008) and are summarized in Table 1. Beside these theoretical definitions, it is also worth considering how they are implemented in the DANE software, in order to better clarify their underlying significance.

The ***Function*** is defined by means of four (three main mandatory and one optional) elements (Design & Intelligence Laboratory – Georgia Tech, 2011):

- *Verb* associated with the function.
- *Subject* of the function (i.e., the function carrier).
- *Object*(s) of the function (the recipients of the function).
- *Preposition*(s) (describing the environment or particular conditions/requirements), and *Adverb*(s) (such as "quickly," "efficiently," or "stealthily") can be added to describe the function in more detail.

The specification of these elements shows that function definition in DANE is close to the classical < Verb > < Noun > schema (Pahl et al., 2007), and to some related

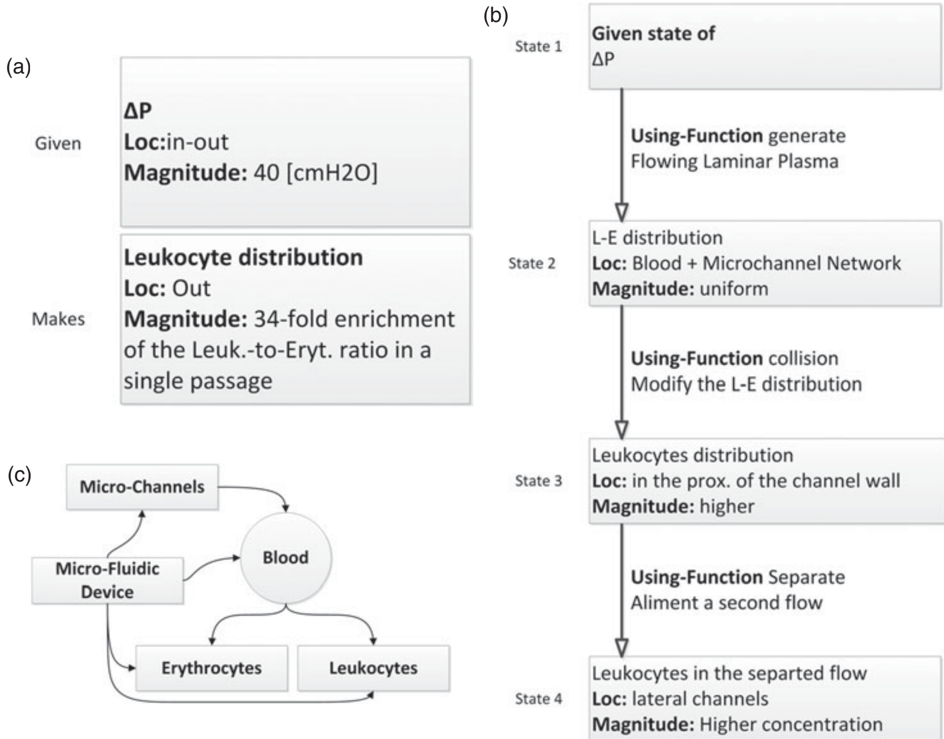

Figure 1. Sample DANE model: Function (left), Behavior (center) and Structure (right). Models extracted from Baldussu et al. (2012).

evolutions (Rosa et al., 2011). Nevertheless, this way of storing function definition does not seem in contrast with the theoretical definition. It allows describing what the system "makes," starting from a "given" initial condition (precondition).

Table 1. DANE model main elements definition.

Structure	In SBF models, structure is represented in terms of components, the substances contained in the components, and connections among the components. The specification of a component includes its functional abstractions, where a component can have multiple functions. The specification of a substance includes its properties. Substances can be abstract, e.g., angular momentum.
Function	A function is represented as a schema that specifies its preconditions and its postconditions. The function schema contains a reference to the behavior that accomplishes the function. This schema may also specify conditions under which the specified behavior achieves the given function (e.g., an external stimulus).
Behavior	A behavior is represented as a sequence of states and transitions between them. The states and the transitions are represented as state and transition schemas, respectively. The states in a behavior specify the evolution in the values of the parameters of substances and/or components. Continuous state variables are discretized, and temporal ordering is subsumed by causal ordering. Each state transition in a behavior is annotated by the causes for the transition. Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behavior.

According to its theoretical definition, the behavior is represented by means of a state-transition diagram. This representation provides a causal explanation of system "functioning," describing how it evolves to reach its goal (accomplish function). Each state is described by a set of physical properties of the parts (i.e., a set of (object:property: value) triplets, so that it is possible to link each property to the relevant part), while the causal explanations of each transition can be one of the following: external stimulus, structural connection, principle, function, and transition.

The Structure is represented by means of a diagram showing "the set of objects related to the system and their relationships, as of the initial state of the system. Objects are represented as boxes, relationships between objects as arrows with annotations representing the kind of connection relationship" (Design & Intelligence Laboratory – Georgia Tech, 2011). The objects and the annotations do not follow any prescription and can be arbitrarily defined by the user.

2.4 Causal models: SAPPhIRE

Chakrabarti et al. (2005) developed "a generic model for representing causality of natural and artificial systems" to "structure information in a database of systems from both domains." They developed a causal language (the acronym of which is SAPPhIRE) to describe structural and functional information of natural and technical systems. This language was conceived to put in evidence the sequence of physical phenomena governing the "functioning" of the system. In other words, SAPPhIRE was designed to put the emphasis on the causal relationships among the phenomena that guarantee the delivery of a system function.

In the SAPPhIRE model (see Figure 2), it is assumed that an external *input* together with a particular "configuration" (called *organ*) of the system (simply described by the list of its *parts*) activate a *Physical Effect*, that results in a *Physical Phenomenon* capable to change the *State* of the system. This causally related sequence of elements is suitable to describe any change of state. Normally, it is used to describe the "main" change of state of the considered system (interpreted as the desired *Action*).

Starting from the first paper published in 2005 (Chakrabarti et al., 2005), Chakrabarti and his research group continuously improved and extended the SAPPhIRE model as documented by several publications: they improved the definitions of the main components of the model, and introduced and continuously enriched the definitions of the secondary[3] elements of the model.

Table 2 summarizes the evolution of the definitions of the main components of the model. The definitions are extracted from the papers cited in the first row and are ordered chronologically from left to right.

Actually, the definitions of *Parts* and *Action* did not undergo a significant evolution. Besides, in the definition of *State*, any reference to time (or instant) disappeared in 2010. This evolution is in accordance with the main scope of the SAPPhIRE model, that is to represent the causal relationships that justify the system functioning. In this perspective, the description of the time dynamics within the system becomes less important.

It can be noticed that the definition of *Organ* evolved from the "structural context" required for an interaction, toward the "properties and conditions" required for an interaction. In principle, these two definitions do not seem to conflict to each other, but the first is useful to better understand the latter. The "properties and conditions" of system and surrounding environment are not only specific properties (the temperature of a part, for example), but can refer also to connections between different parts and to the possibility of interaction between them. These reflections comply with the use of Organ to represent the

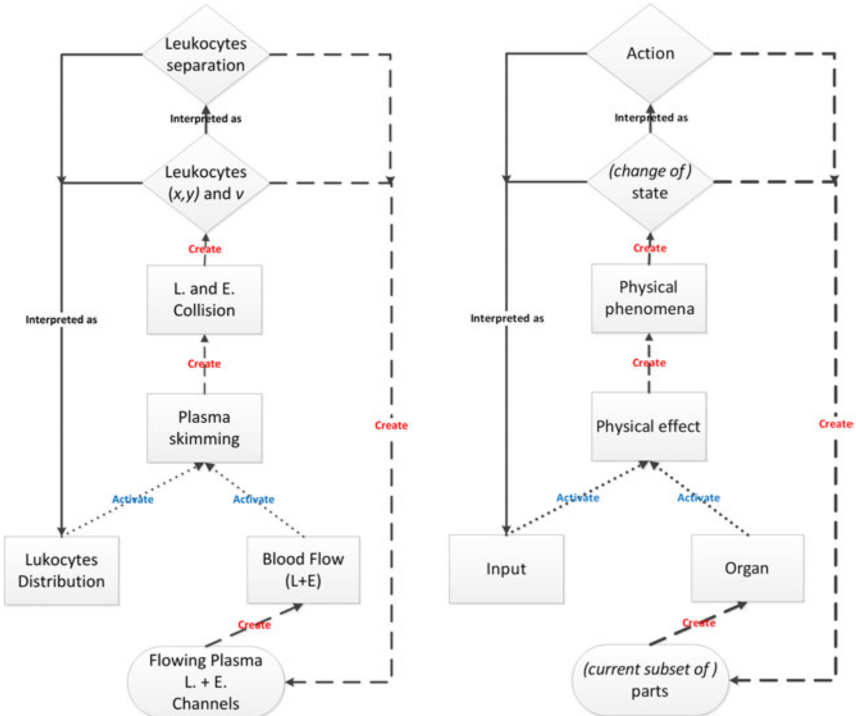

Figure 2. Example instance of SAPPhIRE model and its structure.

system structure, as proposed by the authors of the model in Srinivasan, Chakrabarti, and Lindemann (2012). It is also worth noting that the environment is explicitly mentioned, recognizing its fundamental importance in biological phenomena (Rosa et al., 2011; Vattam, Wiltgen, et al., 2010).

Analyzing *Input* definitions, it can be concluded that an *Input* is a particular property of the environment that triggers the *Physical Effect*, thus producing the *Physical Phenomenon*; as such, the *Input* should be distinguished from the system properties that enable the *Physical Effect* and are described by the *Organ*.

In fact, the *Physical Effect* is the general principle underlying the *Physical Phenomenon*. The *Effect* can be considered as the abstract description of the physical principle (i.e., its theoretical laws and governing equations), while the *Phenomenon* is the practical embodiment of the *Effect*, conditioned by the actual properties of the physical system (*Organ*). In other words, the peculiar condition and configuration of the system (*Organ*) grants only the possibility that a *Phenomenon* occurs according to a specific physical principle (*Effect*), but not its actual occurrence, that is conditioned to a triggering event (*Input*).

In the following sections, the latest definition (Sartori et al., 2010) will be adopted as the reference.

3. DANE and SAPPhIRE through practical examples

With the aim of clarifying the motivation of the following analysis of DANE and SAPPhIRE, this section presents two examples of bio-inspired products extracted from the

Table 2. SAPPhIRE model main elements definition.

Reference	A functional representation for aiding biomimetic and artificial inspiration of new ideas – 2005[a]	Gems of SAPPhIRE: a framework for designing? – 2007[b]	SAPPhIRE – an approach to analysis and synthesis – 2009[c]	Development of a catalogue of physical laws and effects using SAPPhIRE model – 2010[d]	A methodology for supporting transfer in biomimetic design – 2010[e]	Towards an ontology of engineering design Using SAPPhIRE model – 2012[f]
Parts	A set of physical components and interfaces constituting the system and its environment of interaction	A set of physical components and interfaces constituting the system and its environment of interaction	A set of physical components and interfaces constituting the system and its environment of interaction	Physical elements and interfaces that constitute the system and the environment.	A set of physical components and interfaces that constitute the system of interest and its environment	A set of components and interfaces that make a system and its environment
State	The attributes and values of attributes that define the properties of a given system at a given instant of time during its operation	The attributes and values of attributes that define the properties of a given instant of time during its operation	The attributes and values of attributes that define the properties of a given system at a given instant of time during its operation	A change in property of the system (and the environment) that is involved in the interaction	A property of the system (or its environment) that is involved in an interaction	A property of a system (and its environment) due to an interaction
Organ	The structural context necessary for a physical effect to be activated	The structural context necessary for a physical effect to be activated	The structural context necessary for a physical effect to be activated	Properties and conditions of the system and the environment required for the interaction	A set of properties and conditions of the system and its environment required for an interaction between them	A set of properties and conditions of a system and its environment that are also required for an interaction
Effect	The laws of nature governing change	The laws of nature governing change	The law of nature governing a change	A principle that governs the interaction	A Principle of Nature that underlies and governs an interaction	Principle underlying an interaction

(*Continued*)

Table 2 – *continued*

Reference	A functional representation for aiding biomimetic and artificial inspiration of new ideas – 2005[a]	Gems of SAPPhIRE: a framework for designing? – 2007[b]	SAPPhIRE – an approach to analysis and synthesis – 2009[c]	Development of a catalogue of physical laws and effects using SAPPhIRE model – 2010[d]	A methodology for supporting transfer in biomimetic design – 2010[e]	Towards an ontology of engineering design Using SAPPhIRE model – 2012[f]
Input	The energy, information, or material requirements for a physical effect to be activated; interpretation of energy material parameters of a change of state in the context of an organ	The energy, information or material requirements for a physical effect to be activated; interpretation of energy/ material parameters of a change of state in the context of organ	The energy, information or material requirements for a physical effect to be activated; interpretation of energy/ material parameters of a change of state in the context of an organ	A physical quantity in the form of material, energy or information that comes from outside the system boundary and is essential for the interaction.	A physical variable that crosses the system boundary and is essential for an interaction between the system and its environment	Physical quantity that comes from outside the system boundary that is required for an interaction
Physical phenomenon	A set of potential changes associated with a given physical effect for a given organ and inputs	A set of potential changes associated with a given physical effect for a given organ and inputs	A set of potential changes associated with a given physical effect for a given organ and inputs	An interaction between a system and its environment	An interaction between the system and its environment	An interaction between a system and its environment
Action	An abstract description or high-level interpretation of a change of state, a changed state, or creation of an input	An abstraction description or high-level interpretation of a change of state, a changed state, or creation of an input	An abstract description or high-level interpretation of a change of state, a changed state, or creation of an input	An abstract description or high-level interpretation of the interaction	An abstract description or high-level interpretation of an interaction between the system and its environment	An abstract interpretation of an interaction

[a] Chakrabarti et al. (2005).
[b] Srinivasan and Chakrabarti (2007).
[c] Chakrabarti and Srinivasan (2009).
[d] Srinivasan and Chakrabarti (2010).
[e] Sartori et al. (2010).
[f] Taken from Srinivasan and Chakrabarti (2010) and Srinivasan et al. (2012).

field literature. In order to ensure impartiality in this comparison, these examples do not belong to any of the papers directly related to the DANE or the SAPPhIRE models. By comparing these examples, it is possible to appreciate the complementary characteristics of the information these models can represent.

The comparison of the type of information represented by the two models has been based on the following questions:

- *How the achievement of the system's function is represented?*
- *How the changes of states and their sequence, which accomplish the system's behavior, are represented?*
- *How the regenerative behaviors are represented?*
- *How the parts and the relations among the parts are represented?*

3.1 Case study 1: reversible switching of hydrogel-actuated nanostructures into complex micro-patterns

The first selected case study is a dynamic actuation system obtained by integrating high-aspect-ratio silicon nano-columns with a hydrogel layer forming a functional surface. This device is based on the principles of nano and micro structures that can be found in many natural systems (such as gecko feet, lotus leaves, and cicada and butterfly wings); these structures can provide these organisms with exceptional properties (e.g., adhesive, self-cleaning, water-repelling, and photonic).

In fact, these systems realize a "responsive behavior," an intrinsic feature of natural systems that is becoming one of the key requirements of advanced artificial materials and devices (Figure 3).

The specific bio-inspired product analyzed here

> relies on the combination of soft (hydrogel) and hard elements (array of isolated, high–aspect-ratio rigid structures, AIRS) to obtain the reversible actuation of rigid surface nano- and micro-structures that are set in motion by the polymer layer. The AIRS provide rigidity, structure, and precision, whereas the hydrogel provides responsive behaviour (Description extracted from Sidorenko, Krupenkin, Taylor, Fratzl, & Aizenberg, 2007).

Figure 4a shows the SAPPhIRE model of the Reversible switching of hydrogel-actuated nanostructure. A given level of ambient humidity (*"Input"*) in the chemical bonds (*"Part"*) chemically react (*"Physical Effect"*), and changing the molecular structure of the hydrogel (*"Physical Phenomena"*) makes a variation in the orientation of the high-aspect-ratio silicon nano-columns (*"State"*). This results in a change of the surface characteristics (*"Action"*).

Figure 4b shows the three main parts of the DANE approach: from the top to the bottom, respectively, the *Function* representation of the system, the *"Behavior"* model of the whole process, and the *Structure* of the system.

3.2 Case study 2: ternary coupling Bionic Bit

The second selected case study is an impregnated diamond-coupling bit (Figure 5), which is a renascent nonsmooth framework (three dimensional), which allows improving the penetration rate and the life of impregnated diamond bits. This device is based on the coupling of physical and chemical features of nonsmooth shape and materials inspired by natural surfaces such the Dung Beatle tergum.

Practically, this system reproduces the reinforcement in the excavation capacity of the Dung Beatle head. This surface morphology reduces the contact area during the relative movement in the soil. "The concave non-smooth shape exists almost in all the sites where

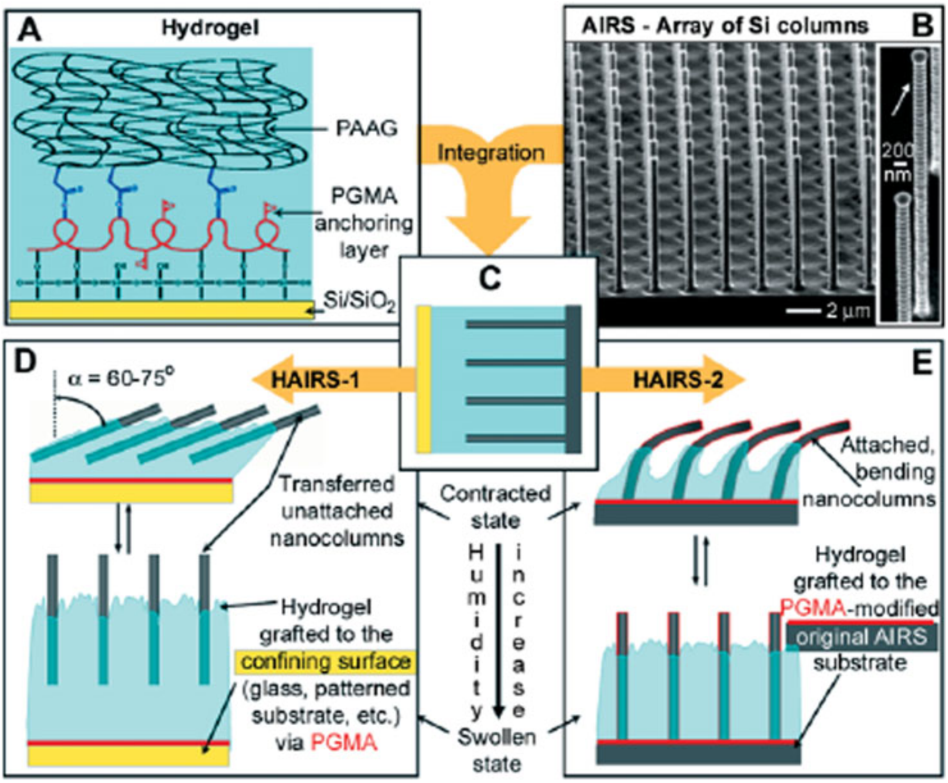

Figure 3. Schematic representation of the bio-inspired product. Courtesy by picture extracted from Sidorenko et al. (2007).

the soil is loose with low cohesion and interface pressure, but using the non-smooth features the concave pits are able to reduce the contact area and improve the excavation also in hard terrains" (Description extracted from Gao et al., 2008).

Figure 6a shows the SAPPhIRE model of the Bionic Bit. A given torque (*"Input"*) on the steel body (*"Part"*) together with the morphological characteristics of the alternative self-generation non-smooth structure (*"Organ"*) makes a wear and tear process (*"physical phenomenon"*), which creates a friction (*"Physical Effects"*) that generate surface consumption (*"State"*), which in turn makes the regeneration of the non-smooth surface (*"Action"*).

Figure 6b shows the three main parts of the DANE approach. The upper part of the picture shows the *Function* representation of the system, then the central part illustrates the *"Behavior"* model of the whole process of the device. The bottom part of the picture shows the *Structure* of the system.

3.2.1 Comparing the information represented using the SAPPhIRE and the DANE models

The presented examples show how causal and functional models can be used to represent different aspects of the natural systems used as a source of inspiration for the development of technical solutions.

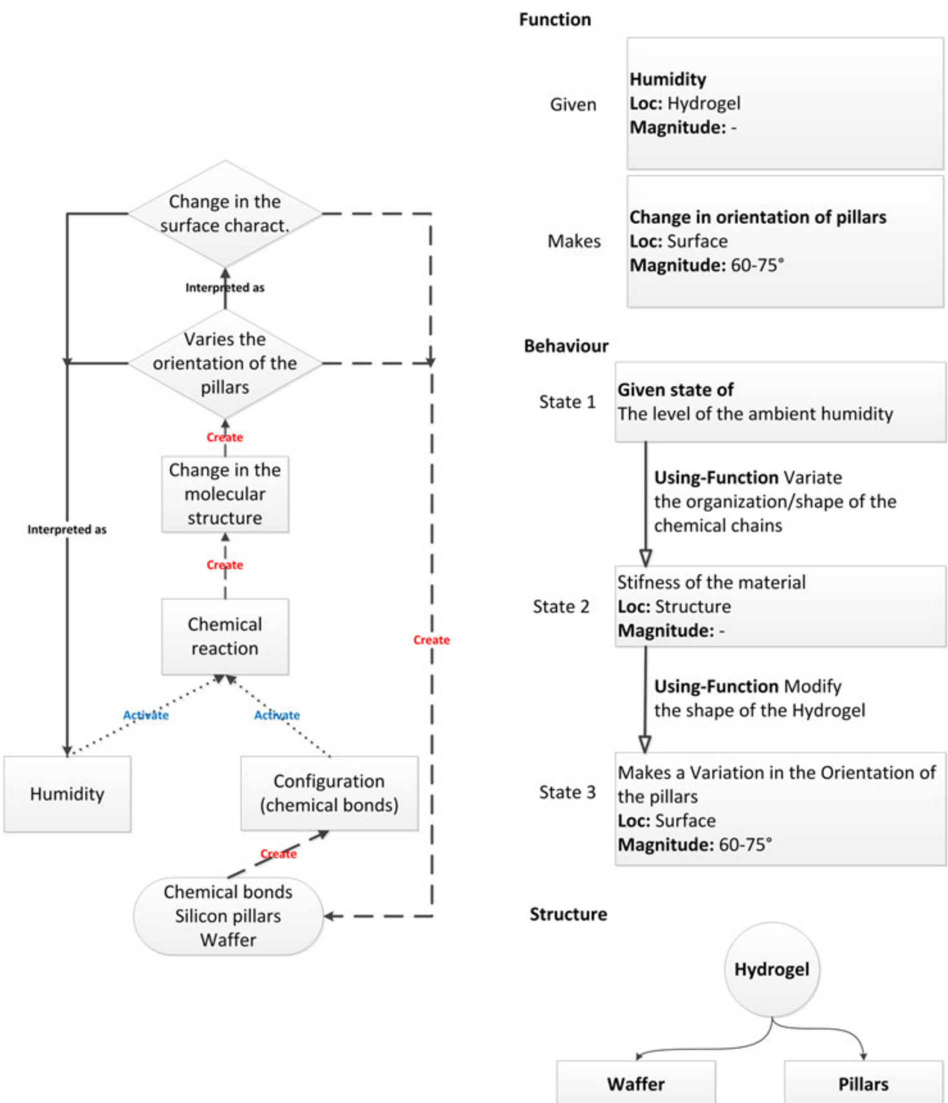

Figure 4. (Left) SAPPhIRE model and (Right) DANE model of the Reversible switching of hydrogel-actuated nanostructure.

In both cases, some surface features are implemented. Obviously, these two materials have different features that are connected to different functions and behaviors realized by the two natural systems.

An evaluation of the potential loss of innovation, which is an incomplete description of the natural system implies, can be achieved by considering that, according to Howard, Culley, and Dekoninck (2008), the originality increases by innovating, respectively, Structure, Function, and Behavior.

In the first case study, the reversibly switching functional surface, the SAPPhIRE model does not represent the behavior of the system thoroughly, because it misses to represent the complete sequence of states. The main function of the system is achieved by a specific sequence of changes of states. Each state change is obtained by a specific

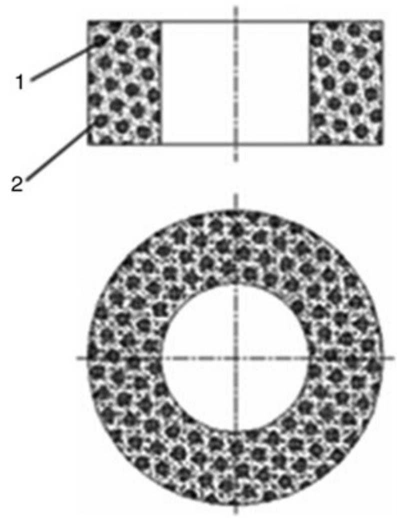

Figure 5. Schematic representation of the bio-inspired product. Picture extracted from Gao et al. (2008).

response of the parts that create the whole technical implementation. All these aspects are represented adequately using the DANE modeling approach, because for each state it also gives the information about the involved part.

Furthermore, in order to properly represent the ability of the functional surface of changing the orientation of the "technical hairs," it is fundamental to have a proper description of the structure of the system, because the behavior relies on the mutual relations among parts. In the SAPPhIRE model, the structure is represented as a list of parts. Actually, both the approaches show that the description of the structure is not completely adequate, due to a lack of a formal and univocal description of the type of the relations among components, despite the DANE model appears as more complete.

In the second case study, the Ternary Coupling Bionic Bit, the predominant feature implemented in the technical solution is the morphological characteristic of the surface, which is renewed by a regenerative behavior of the system. Both modeling approaches seem incomplete to represent the specific features of the surface and their evolution. In any case, the *"Organ"* of the SAPPhIRE model allows a satisfactory description of the parts' features that are important for the activation of the *"Physical Effect."* In the DANE model, this morphological characteristic is not explicitly represented.

Another fundamental aspect, strictly related to the characteristics of natural systems, i.e., the regenerative capabilities of the features of the system, can be explicitly represented using the SAPPhIRE approach, as depicted by the "create" link between *action* and *parts*. On the other hand, the DANE model is not able to represent this "close loop," which allows the regeneration of the surface. This happens because there is no connection between the main function of the system and the input, which allows representing the regenerative behavior of the system.

In fact, the two case studies show that the SAPPhIRE model does not represent with sufficient degree of detail the relationships among system components and the different state changes characterizing the behavior that allow the system to deliver the main function.

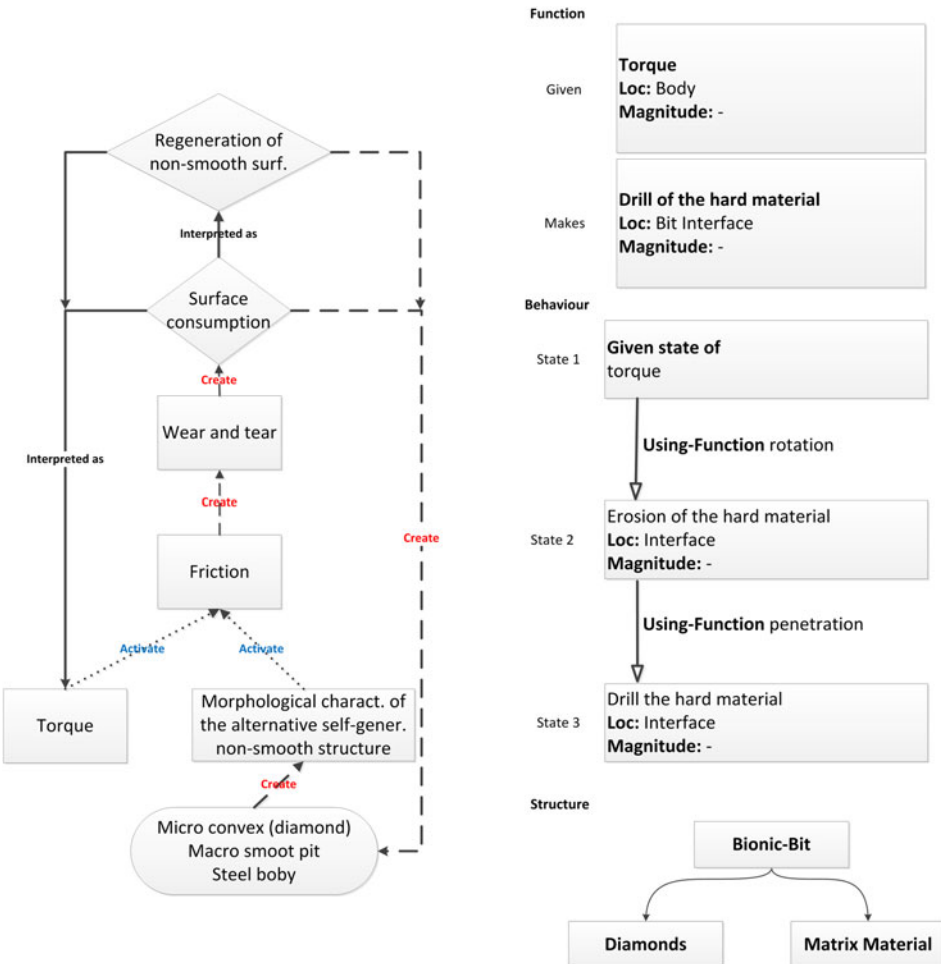

Figure 6. (Left) SAPPhIRE model and (Right) DANE model of the Bionic Bit.

On the other hand, DANE does not allow representing any self-regenerative phenomenon and the morphological characteristic of the system. Both these aspects are extremely important in nature and widespread in a big number of natural systems.

The pieces of information represented by these two models are complementary and allow describing more completely Nature's solutions in order to increase the number of aspects that can be implemented into a bio-inspired product and ensure a complete exploitation of all the categories of engineering information described by Howard et al. (2008).

In the authors' vision, an integrated model leveraging the current potential of the DANE and the SAPPhIRE modeling approaches can suitably address the representation of natural systems and phenomena suitable for bio-inspired structures and materials, mechanisms and processes, behaviors and controls, and sensors and communications. Such modeling domain can be represented according to the classification of the Biomimetic Technology Tree proposed by PB Works – Biomimetic (2009). In detail, the modeling domain of the integrate model is represented by the empty cells in Table 3.

Table 3. Modeling domain.

	Scale									
Biomimetic technology tree	2.2–2.6 (nm) DNA	0.3–300 (nm) Macro-molecules	5–10 (nm) Organelle	5–20 (μm) Cells	2–20 (mm) Tissues	8 (mm)–30 (cm) Organs	50 (cm)–9.1 (m) Systems	10 (nm)–83.8 (m) Organisms	Populations	Ecosystems
Structures and materials									–	–
Mechanisms and processes									–	–
Behaviors and controls									–	–
Sensors and communications									–	–
Generation biomimicry	–	–	–	–	–	–	–	–	–	–

The main aim of the authors' research is the development of an integrated functional-causal model suitable to describe any natural system in the perspective of transferring knowledge for bio-inspiration. In order to succeed in this goal by exploiting the significant achievements by SAPPhIRE and DANE developers, it is fundamental to carry out a study of the morphological characteristics of their components, the formal relations among the components, and the definitions of each component. This analytical comparison is the main objective of the next section.

4. Comparing the ontologies of DANE and SAPPhIRE

The examples discussed in the previous section show that none of the two modeling approaches is sufficient to cover the entire spectrum of potentially relevant types of information meaningful for BID. On the other hand, they have been both developed and tuned with satisfactory results in the last decade. Therefore, it is useful to assess their complementarity and potential mutual coherence in the perspective of building an integrated model within a single framework. With this perspective, this section proposes a detailed comparison of the ontologies of the two models.

4.1 DANE and SAPPhIRE ontology

A recursive approach has been adopted to derive the ontology of these two modeling techniques. First, all the explicit definitions provided by the authors of DANE and SAPPhIRE have been identified, collecting all the references to the model elements available in literature. Whenever an explicit definition of a secondary element was missing, it was assumed that the authors attributed to the term its ordinary definition semantically significant in the context. For these terms, the Oxford English Dictionary (OED) was adopted as the basic reference, despite a small number of terms required a new definition, as detailed below, so as to guarantee a proper coherence with the other terms of the two models. This procedure has been reiterated with the obtained definitions, until a "basic" level has been reached, i.e., a level such that the definitions make use only of general language terms and do not require any further explanation.

This procedure allows to automatically structure the model's ontology in hierarchical levels: level 0 is the basic level, level i contains all the terms whose definitions require terms of level $i-1$ only, and so on, up to the level containing the definitions of the primary elements of the model.

Furthermore, this procedure allowed defining all the semantic relationships between the terms; it was possible therefore to draw a semantic tree of the elements of the model.

For example, the SAPPhIRE definition of *State* refers to:

a <u>property</u> of the <u>system</u> (or its <u>environment</u>) that is involved in an <u>interaction</u>.

The underlined words have been identified as semantically relevant to define *State* ontology.

First, each of these terms was searched within all the related papers. Interaction, System, and Environment were defined in Chakrabarti and Srinivasan (2009), while a precise definition of the element *Property* was not provided in the considered papers. The OED definition appears coherent with the meaning of the other terms of the models and as such it has been added to the ontology as well.

The result of the first step is the following list of definitions:

- *Property*: "An attribute, characteristic, or quality of the <u>universe</u>" and/or of any of its parts (based on [OED]).

- *Interaction*: "It is the communication between a system and its environment with each other to reach equilibrium. The equilibrium here refers to a balance in the properties of the system and environment. A system and its environment try to attain equilibrium because it is the most stable condition. It is governed by effects" (Chakrabarti & Srinivasan, 2009).
- *System*: "A subset of the universe which is under consideration. A system is characterized by its boundary called the system boundary" (Chakrabarti & Srinivasan, 2009).
- *Environment*: "All the other subsets of the universe apart from the system constitute the environment" (Chakrabarti & Srinivasan, 2009).

It is then possible to reiterate the analysis procedure with the semantically characterizing (underlined) words in these definitions. The same procedure was initiated for each primary element of SAPPhIRE and DANE. As anticipated above, the analysis is halted when a component is defined only through basic and/or common sense terms.

In both models, all the primary elements are obviously explicitly defined by the authors. *State* is the only term shared by DANE and SAPPhIRE, and the two definitions seem to be in good agreement for the following terms:

On the other hand, only some of the secondary terms are explicitly defined, and more precisely the followings:

- SAPPhIRE: System, Environment, Interaction.
- DANE: Connections, Element, States, Variables, Components, Structure Model, Transition, State transition, Stimuli, Functional abstraction, Function schema.

It was possible to adopt the OED definition for many of the other secondary terms (the italic terms are shared by the two models):

- SAPPhIRE: *universe*, *condition*, *property*, interface, law of nature.
- DANE: cause, *condition*, device, fluid, force, purpose, *universe*, causal, *property*, substance, *environment*, precondition.

The definition of "Environment" can be assumed to be equivalent in both models, because the SAPPhIRE definition is practically identical to the OED definition.

Nevertheless, the OED definitions revealed to be not appropriate to define all the secondary terms, because of the specific semantic connotation of these terms. It was therefore necessary to conceive a specific definition for some of the secondary terms (listed in Table 4).

Figures 7 and 8 show the resulting conceptual maps.

Table 4. secondary terms proposed definitions.

Terms	Definition	Model
Physical component	An atomic-level element of the system	SAPPhIRE
Boundary	The border that separates the system and the environment	SAPPhIRE
Physical variable	A model of a property of the system or of the environment characterized by a symbol and a value or a set of values that constitute the instantaneous instance of the model	SAPPhIRE
State variable	Variables used to define a state	DANE
Connecting Point	Portion of an element through which it interacts with other elements	DANE
System	A subset of the universe that is under consideration.	DANE
Postcondition	A condition that is fulfilled after something happened	DANE

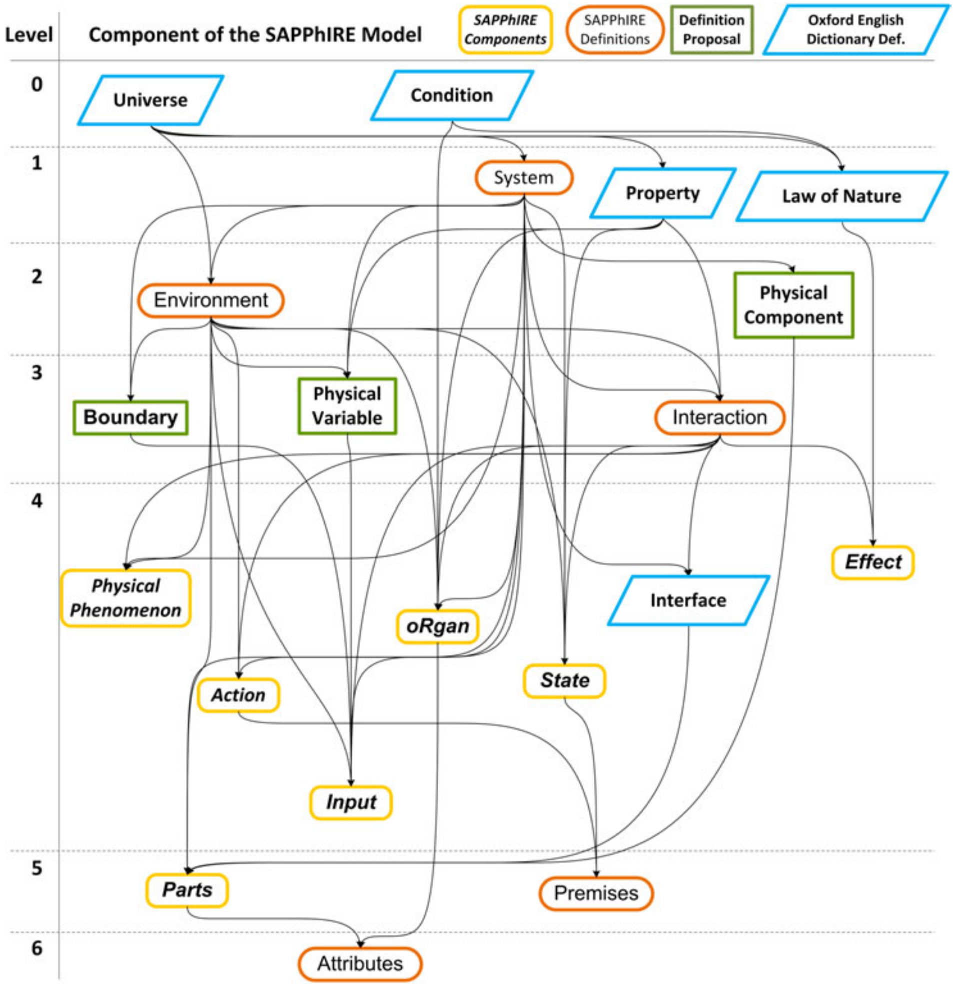

Figure 7. SAPPhIRE conceptual map.

Even if the number of DANE primary elements is smaller than those belonging to SAPPhIRE, its conceptual map results in more hierarchical levels. In turn, this may indicate a higher level of abstraction of DANE primary elements. This consideration is in accordance with the observation in Srinivasan et al. (2012), where it is noted that each DANE element requires at least two SAPPhIRE elements to be described (Function includes action, state change,[4] and input; Behavior includes phenomenon and effect; Structure includes organ and part).

Besides, DANE ontology presents recursive definitions and loops. For instance, the definition of the term "component" makes use of the words "element" and "connection," but the definition of the latter requires that "component" has been already defined. The connections represented by means of dashed lines in Figure 8 reveal a recursive definition.

Furthermore, in DANE, the term "stimuli" is not explicitly defined, but it can be derived through an implicit description: "The final constituent of an SBF Model describes the environmental Stimuli that can affect its Behavior" (Goel et al., 2008).

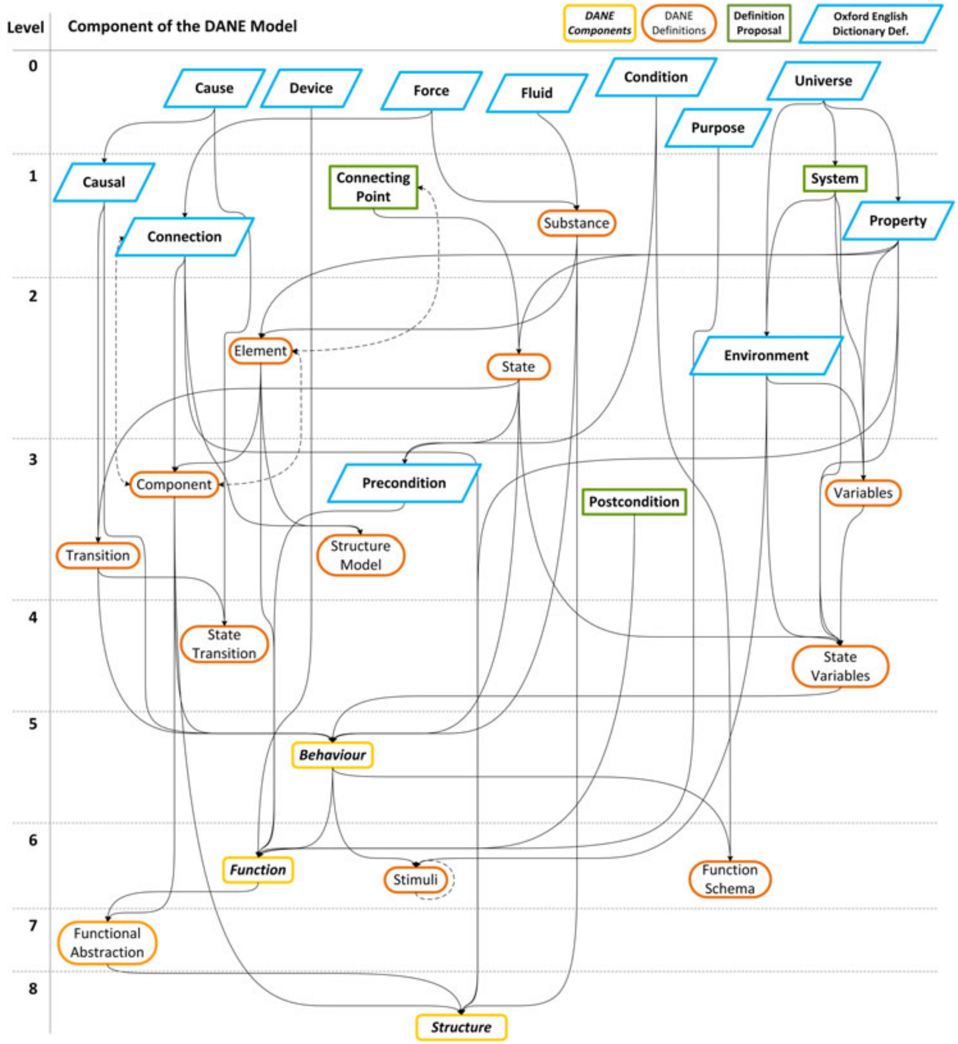

Figure 8. DANE conceptual map.

4.2 DANE and SAPPhIRE structure and ontology comparison

In the previous section, the ontology of the DANE and SAPPhIRE modeling approaches has been presented and briefly discussed. In order to assess the coherence of the two models and their potential integration, their ontologies are compared in this section.

The comparison has involved all the elements of the two ontologies: the definition of each element of DANE has been compared with all the definitions of the SAPPhIRE elements and vice versa (Table 5), searching for a semantic correspondence.

From the semantic point of view, the comparison between two elements can bring three different results:

- YES, if there is a full semantic correspondence between the two elements.
- PARTIAL, if the two elements definitions overlap only partially.
- NO, if there is no relation between the two elements.

In actuality, the full correspondence occurred only with some secondary terms.

Besides, it is important to observe that no conflicting definitions have been observed. In other words, the same term has never been used in the two models to indicate two different concepts, and (more important) in any case the same concept has never been defined including contrasting requirements, details, or subelements.

In fact, the comparison reveals several PARTIAL correspondences consisting of different partial mismatches:

i. the same element is used in a different way and/or context in the two models, hence one or more "details" are added/removed.
ii. a single element in one model is subdivided into several "subelements" in the other model.

In more detail, looking at the primary elements of the two models, SAPPhIRE, misses to explicitly define *Structure*. It is worth noting that this is the consequence of the relative nature of Behavior in SAPPhIRE, defined as the link between Function and Structure (Chakrabarti et al., 2005). This means that, depending on what is taken as Structure and Function, the concept of Behavior may change in the "original" SAPPHiRE model. Nevertheless, in order to make the comparison between the two DANE and SAPPhIRE clearer, the correspondences defined by Chakrabarti some year later (Srinivasan et al., 2012) are adopted hereafter. The authors also state that "Structure is described by the elements and interfaces of which the system and its immediate, interacting environment are made" (Chakrabarti et al., 2005). In order to find a correspondence of this definition within the DANE model, it is possible to refer to the terms "element," "interface," and "environment." Indeed, the definition of "interface" does not resemble any term of the DANE model. On the other hand, it is possible to recognize a certain degree of overlap between the meaning of the terms "element" (DANE) and "physical component" (SAPPhIRE). It is also worth remembering that the definition of *Organ* proposed in previous papers (Baldussu, Cascini, Rosa, & Rovida, 2012) explicitly refers to the structural aspect.

Comparing the definition of *Function* (DANE), it can be concluded that the pre- and postconditions can be described by means of the first and last system states (assuming that in function description, only initial and final states are considered) and that *Input* is a particular "element" of the initial state, essential for the process. The *Action* is the comprehensive interpretation of system transition from initial to final state.

Analyzing Behavior's meaning in DANE, a partial correspondence between *Behavior* (DANE) and *Physical Phenomenon* (SAPPhIRE) has been recognized: a *Physical Phenomenon* ("an interaction between the system and its environment") can be used to describe the behavior of the system. It seems reasonable to recognize also a partial correspondence between *Effect* and *Behavior*, because *Effect* is the abstract Principle of Nature that embodies in a specific physical phenomenon.

In order to assess this comparison, Tables 6–8 show the definitions of the DANE and SAPPhIRE primary elements for which a partial correspondence has been recognized. It is worth noting that these correspondences are in agreement with Srinivasan et al. (2012).

Furthermore, in DANE, even if the definition of "Structure" does not contain any reference to properties, an object description is associated to each element of the structure in its practical implementation. This description is where the properties of objects are stored: "These are the properties associated with the objects in the states found in the behavior diagram. Objects can have *parent* and *child* hierarchical relationships allowing property inheritance" (Design & Intelligence Laboratory – Georgia Tech, 2011), even

Table 5. Comparison of models terms.

			Cause	Condition	Device	Environment	Fluid	Force	Purpose	Universe	Causal	Connections	Connecting Point	Properties	Substance	System	Element	States	Variables	Components	Postconditions	Preconditions	Structure Model	Transition	State transition	State variables	Stimuli	Fuctional abstraction	Behaviour	Function	Structure	Function schema
			OED	OED	OED	SAPPhIRE 2009	OED	OED	OED	OED	OED	The structure, behavior, and function modeling language - 2009	Author's proposal definition	OED	OED	Author's proposal definition	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	Author's proposal definition	OED	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	Author's proposal definition	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009	The structure, behavior, and function modeling language - 2009
			0	0	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2	3	3	3	3	3	4	4	6	7	5	5	8	6
OED	0	Universe	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
OED	0	Condition	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P	N	N	N	N	N	N	N	N	N	P
OED	1	property	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SAPPhIRE 2009	1	System	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Encyclopædia Britannica	1	Principle of nature	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Author's proposal definition	2	Physical component	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N
SAPPhIRE 2009	2	environment	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Author's proposal definition	3	Boundary	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Author's proposal definition	3	physical variable	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N
SAPPhIRE 2009	3	interaction	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
OED	4	Interface	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SAPPhIRE AI EDAM 2010	4	**State**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	P	N	N
SAPPhIRE AI EDAM 2010	4	**oRgan**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	N	P	N
SAPPhIRE AI EDAM 2010	4	**Effect**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N	P	N	N	N
SAPPhIRE AI EDAM 2010	4	**Input**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	P	N	N
SAPPhIRE AI EDAM 2010	4	**Physical phenomenon**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N
SAPPhIRE AI EDAM 2010	4	**Action**	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N
SAPPhIRE AI EDAM 2010	5	**Parts**	N	N	N	P	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N
SAPPhIRE AI EDAM 2010	5	Premises	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SAPPhIRE AI EDAM 2010	6	Attributes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 6. DANE–SAPPhIRE structural elements comparison.

DANE		SAPPhIRE	
Structure	Structure is represented in terms of components, the substances contained in the components, and connections among the components	Organ	A set of properties and conditions of the system and its environment required for an interaction between them
		Parts	A set of physical components and interfaces that constitute the system of interest and its environment

though it may also have its own unique properties. Practically, properties are stored in both models, but in SAPPhIRE more emphasis is put on the properties that are required for *Physical Phenomenon* and *Effect*, while in DANE they are "hidden" behind each object in the structure.

Looking at the functional elements (Table 7), SAPPhIRE definitions allow assigning a precise role to elements, easing information retrieval and system understanding; all these elements seem to be storable also in the practical implementation of DANE function definition. In particular, Verb, Subject, Object(s), Preposition, and Adverbs can be mapped onto SAPPhIRE action, while first and last states can correspond to pre- and postconditions. The Input element is a peculiarity of SAPPhIRE that, to some extent, can be embedded in DANE precondition, because it is "something" external to the considered system.

Correspondences shown in Table 8 differ from those proposed in Srinivasan et al. (2012), because intermediate system States have been reputed necessary to describe system behavior. It is worth noting that in a SAPPhIRE diagram, intermediate states are not usually considered, because it is possible to represent only one change of state. Nevertheless, an attempt to introduce also intermediate Sates is presented in Sartori et al. (2010) by describing the system (prairie dog dean) with two separate and consecutive SAPPhIRE diagrams, even if the authors did not provide any hints on how to connect them.

Coming to the secondary terms, many full correspondences have been recognized, especially for lower levels terms. The main reason of these results is that practically none

Table 7. DANE–SAPPhIRE functional elements comparison.

DANE		SAPPhIRE	
Function	A function is represented as a schema that specifies its preconditions and its postconditions	Action	An abstract description or high-level interpretation of an interaction between the system and its environment
		Input	A physical variable that crosses the system boundary and is essential for an interaction between the system and its environment
		State	A property of the system (or its environment) that is involved in an interaction

Table 8. DANE–SAPPhIRE behavioral elements comparison.

DANE		SAPPhIRE	
Behavior	A behavior is represented as a sequence of states and transitions between them.	Effect	A Principle of Nature that underlies and governs an interaction
		Physical phenomenon	An interaction between the system and its environment
		State	A property of the system (or its environment) that is involved in an interaction

of the terms of the lower levels (0, 1, 2) is explicitly and independently defined in both models. Consequently, many of these definitions have been extracted from the OED.

It is also worth considering that only half of the elements defined in only one model can be correlated to a different term of the other model on the basis of its meaning. This result suggests that the two models may share a common basis constituting the founding lexicon to define both of them.

5. The UNified Ontology for BID

The detailed analysis of the ontologies of DANE and SAPPhIRE has demonstrated that the two modeling approaches are complementary and compatible with each other. They can therefore be adopted as the fundamental constituents of a unified ontology suitable for building an integrated framework for BID.

The construction of this unified ontology has been implemented by the authors in Protégé 4.3.0 (Build 304). The graphs depicting the unified ontology have been realized with the OntoGraf plug-in 1.0.1. In these graphs, the entities are represented by rectangular boxes connected by oriented lines. A continuous line represents a "*has subclass*" relationship (Figures 9 and 10), i.e., the entity on which the line terminates is a subclass of the entity from which the line originates. A dotted line represents the property relationship "*defined by*" (Figure 11), i.e., the entity on which the line ends is needed to define the entity from which the line originates.

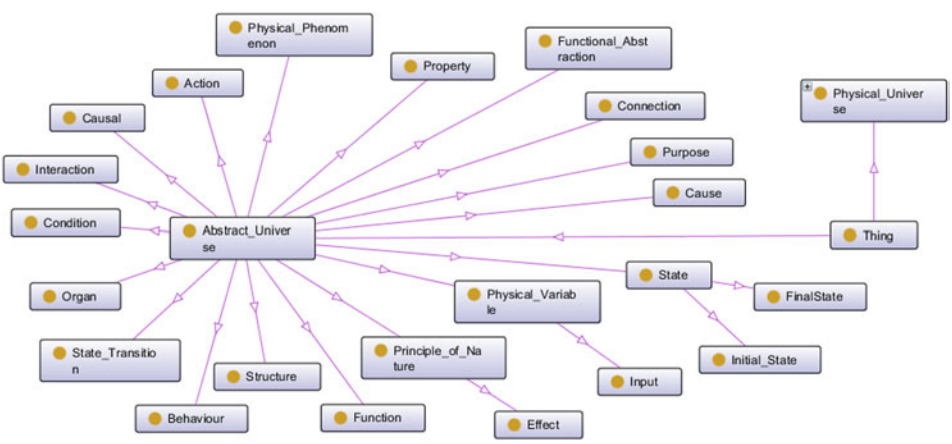

Figure 9. UNO-BID Abstract Universe classes.

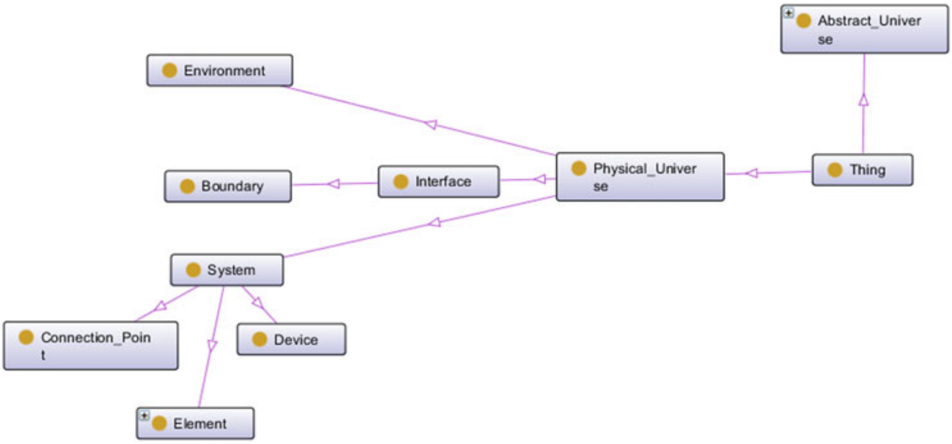

Figure 10. UNO-BID Physical Universe classes.

The UNOBIND constituents have been subdivided into two main groups (classes, in a formal terminology):

- *Abstract Universe*: containing all the things (subclasses) that are an ideal representation (model) of physical objects or abstract concepts, built on the basis of these models.
- *Physical Universe*: containing all the real things.

These classes have been actually defined as subclasses of the predefined (in Protégé) root class *Thing*.

Figures 9 and 10 show, respectively, Abstract and Physical Universe class hierarchy. In the Abstract Universe, the classes have a few "subclass"-type relationships, because this kind of relationships has been used to indicate that entity on which the line ends is a particular type of the entity from which the line originates. In detail, the following subclasses have been individuated:

- *Final State* and *Initial State* are two peculiar *States*.
- The *Input* is a peculiar *Physical Variable*.
- The Effect is a particular *Principle of Nature*.

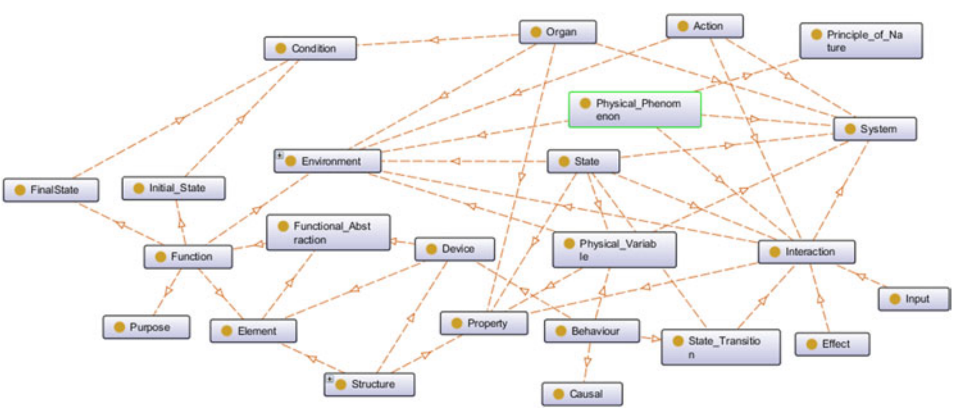

Figure 11. UNO-BID definitions schema.

Three main subclasses have been defined in the *Physical Universe*. The real universe is subdivided into two big main regions: *System* and *Environment*. No further subdivision has been introduced in the *Environment*, while the *System* has been subdivided into *Device* (subassemblies) and *Elements* (parts). The *Device* is defined according to its specific *Functional Abstraction* (Figure 11); in other words, it is defined by its capability to perform a subfunction or an auxiliary function required for the functioning of the system itself. A further subclass *Connection Point* has been defined to identify the portions of devices, elements, and/or environment through which they interact with the others. The sum of the connection points in conjunction with the surfaces limiting devices, elements, and/or environment are the *Interface*. The third subclass of the Physical Universe is the *Boundary* that is the *Interface* between the *System* and the *Environment*.

Table 9 provides the complete list of all the classes and subclasses of UNified Ontology for BID (UNO-BID), together with their definitions. These definitions are based on the SAPPhIRE and DANE models elements; nevertheless, some of them have been modified on the basis of the formal analysis performed in Protege. The leftmost column (Alias) contains the name of the entity in DANE and/or SAPPhIRE, if it differs from the name adopted in UNO-BID.

For the sake of clarity, Figure 11 shows the network resulting from the *Defined By* property of the more abstract entities only, i.e., the Primary components of DANE and SAPPhIRE. Hence, Figure 11 does not represent all the UNO-BID elements, nor all the *Defined By* relationships. Nevertheless, it allows studying the main conceptual relationships among these elements and their practical and theoretical significance.

Several issues previously described can be recognized in these schemas. As an example, the correspondences between the Primary elements of DANE and SAPPhIRE (see Tables 6–8) will be hereafter discussed in detail, in order to highlight how and through which elements these correspondences are established.

According to Srinivasan et al. (2012), *Function* can be represented by combining *Action*, *Input*, and *State*. Actually, as above discussed, *Function* is directly related to *Initial* and *Final State*, because it is focused on the task of the overall system, while the *Behavior* is related to each single *State Transition*, because it is meant to represent system evolution. *Input* is a peculiar *Physical Variable* related to system initial state. *Action* is connected to *Function* thorough the *Interaction* between *System* and *Environment*, where the System has to be considered as a sum of *Elements* (*Element* is a subclass of *System*).

Structure can be represented by merging *Organ* and *Device* (i.e., *Parts*). While the connection between *Structure* and *Parts* is direct, the connection between Structure and *Organ* occurs through the *Property* class that represents also the description of connections among elements of *Device* and *Element* classes.

Finally, *Behavior* was told to be composed of *Effect*, *Physical phenomenon*, and *State*. *Behavior* is connected to *State* in two ways: through *Physical Variable* and *State Transition*, because it is a sequence of *State(s)* (represented by means of the *Physical Variables*) and of transitions between them. Furthermore, *State transition* connects *Behavior* to *Interaction* (which occurs in state transitions) and then to *Effect* (i.e., a *Principle of Nature* that governs an *Interaction*). In turn, the *Effect* is an element needed to completely describe the causality of a *State Transition*. Similar considerations apply to *Physical Phenomenon*, because *Effect* is the abstract *Principle of Nature* that embodies in a specific *Physical Phenomenon*.

Table 9. UNO-BID definitions.

Name	Definition	Alias
Action	An abstract description or high-level interpretation of an interaction between the system and its environment	
Behavior	A behavior is represented as a sequence of states and transitions between them. The states and the transitions are represented as state and transition schemas, respectively. The states in a behavior specify the evolution in the values of the parameters of substances and/or components. Continuous state variables are discretized, and temporal ordering is subsumed by causal ordering. Each state transition in a behavior is annotated by the causes for the transition. Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behavior.	
Boundary	The border that separates the system and the environment	
Causal	A thing implying a cause	
Cause	That which produces an effect; that which gives rise to any action, phenomenon, or condition	
Condition	Something demanded or required as a prerequisite to the granting or performance of something else; a provision, a stipulation	
Connecting point	Portion of an element through which it interacts with other elements	
Connections	Connections are partitioned into categories based on the way in which force is transferred between the corresponding components	
Device	A piece of system that does a particular job	*Parts (SAPPhIRE)*
Effect	A Principle of Nature that underlies and governs an interaction. It is the abstract Principle of Nature that embodies in a specific physical phenomenon.	
Element	An atomic-level element of the system	*Components (DANE), Physical components (SAPPhIRE)*
Environment	All the other subsets of the universe apart from the system constitute the environment. The system boundary demarcates the system from its environment	
Function	A function is represented as a schema that specifies its preconditions and its postconditions. The function schema contains a reference to the behavior that accomplishes the function. This schema may also specify conditions under which the specified behavior achieves the given function (e.g., an external stimulus). Functions in SBF describe the role that an Element plays in the overall operation of a device. They express the purpose or goal of the Element, whereas the Behavior describes how the purpose is accomplished.	
Functional abstraction	The specification of a component includes its functional abstractions, where a component can have multiple such functions	

(*Continued*)

Table 9 – *continued*

Name	Definition	Alias
Input	A physical variable that crosses the system boundary and is essential for an interaction between the system and its environment	*Stimuli (DANE)*
Interface	A surface lying between two portions of matter or space, and forming their common boundary	
Organ	A set of properties and conditions of the system and its environment required for an interaction between them	
Physical phenomenon	An interaction between the system and its environment	
Physical variable	A model of a property of the system or of the environment characterized by a symbol and a value or a set of values that constitute the instantaneous instance of the model	*Variables (DANE)*
Postconditions	A condition that is fulfilled after other things happened	
Preconditions	A prior condition or state. Also, a condition or term that must be fulfilled before other things can happen or be done; a preliminary stipulation, a prerequisite	
Principle of Nature	Laws of nature are of two basic forms: (1) a law is universal if it states that some conditions, so far as are known, invariably are found together with certain other conditions; and (2) a law is probabilistic if it affirms that, on the average, a stated fraction of cases displaying a given condition will display a certain other condition as well. In either case, a law may be valid even though it obtains only under special circumstances or as a convenient approximation. Moreover, a law of nature has no logical necessity; rather, it rests directly or indirectly upon the evidence of experience	
Property	An attribute, characteristic, or quality of the universe and/or of any of its parts	
Purpose	That which a system sets out to do or attain; an object in view; a determined intention or aim	
State	A set of properties of the system (or its environment) that is involved in an interaction	
State transition	Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behavior. State transitions are the results of an interaction among system, elements, devices, and environment.	
State variables	Variables used to define a state	
Structure	In SBF models, structure is represented in terms of components, the substances contained in the components, and connections among the components. The specification of a component includes its functional abstractions, where a component can have multiple functions. The specification of a substance includes its properties. Substances can be abstract, e.g., angular momentum	
System	A subset of the universe that is under consideration.	
Universe	All existing matter and space considered as a whole	

6. Conclusions

The inherent complexity of natural systems practically prevents a direct exploitation of their knowledge in technical field. Among all the models proposed to overcome this obstacle, DANE and SAPPhIRE are receiving the greatest attentions for the consistency and the regularity of their development over the years.

This paper shows that these models are not two alternative frameworks; even more, they are substantially complementary and, as such, can be used as constituent references for an integrated, comprehensive model for BID. More in detail, in the systematic comparison of DANE and SAPPhIRE ontologies, no conflicting definitions or relationships emerged, even if the semantic gap between the two models was very evident. This gap seems to be strictly related to the final goal of the scholars who conceived the models themselves: SAPPhIRE was mainly conceived to represent the causal chain from phenomena to action, while the main scope of DANE is a clearer representation of system behavior, structure, and state transitions.

On the other hand, because both these types of knowledge are possibly needed in the conceptual design stage of a BID approach, it is worth building a model that embeds all this information. In this perspective, this paper tries to build a reference lexicon, grounded in the SAPPhIRE and DANE models and enriched with standard definitions of basic terms selected from the OED. A few custom definitions must be necessarily added to harmonize the different pieces for the construction of an integrated framework.

The proposed ontology (UNO-BID) has therefore been conceived to be compatible with the existing models, but, at the same time, to overcome their limitations and fully exploit their potential. In turn, UNO-BID is not meant to become a tool for designers by itself. On the other hand, it intends to be a conceptual tool to help the research in the BID field, i.e., to help scholars to build new tools and models compliant with the most established functional models in the BID domain. In other words, UNO-BID has been conceived as a common semantic basis in the BID research field, in order to ease BID adoption by unbinding it from specific models and hence making it more flexible and its basic concepts universally shared.

The authors foresee two main perspectives of application of UNO-BID: the construction of a comprehensive model suitable to represent all the information that could be meaningful for bio-inspiration purposes and the development of specific tools focused on specific functions of a BID process, compliant with the UNO-BID ontology and, as such, mutually compatible.

According to the first perspective, the next step of this research activity consists in the definition of an integrated model based on the unified ontology (UNO-BID) proposed in this paper, capable to combine the holistic perspective of the SAPPhIRE representation, with the more detailed description of system internal structure and evolution, as for the DANE modeling approach. A follow-up paper under finalization will present the integrated model together with experimental evidences of its validity.

On the other hand, UNO-BID allows the development of tools specifically tailored for the different stages of a BID process, suitable to ease their accomplishment. For instance, with the aim of overcoming the difficulties that engineers and designers meet while accessing biological information, it might be useful to create a link between the NIST Functional Basis and the Biomimicry Taxonomy. A tool capable to implement such a link, as proposed in Baldussu and Cascini (2011), if built compliantly with UNO-BID, could be easily integrated with other specific tools built on the same ontology, so as to progressively create a modular BID framework.

Acknowledgement

The final part of this work was conducted using the Protégé resource, which is supported by grant GM10331601 from the National Institute of General Medical Sciences of the United States National Institutes of Health (http://protege.stanford.edu).

Notes

1. Email: gaetano.cascini@polimi.it
2. Email: alessandro.baldussu@polimi.it
3. For the sake of brevity, the elements that form the original model will be called *primary*, while all the items needed to define a primary element will be called *secondary*. Elements needed to define secondary elements are still called secondary.
4. More precisely, only the first and the last states are relevant in Function definition. The intermediate changes of state are relevant for the Behavior.

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Appendix: DANE and SPPhIRE ontologies

Tables A1 and A2 show the ontologies resulting from DANE and SAPPhIRE analyses developed in the paper.

Table A1. SAPPhIRE complete ontology.

Universe	All existing matter and space considered as a whole
Condition	Something demanded or required as a prerequisite to the granting or performance of something else; a provision, a stipulation
Property	An attribute, characteristic, or quality of the universe and/or of any of its parts
System	A subset of the universe that is under consideration
Principle of Nature	Laws of nature are of two basic forms: (1) a law is universal if it states that some conditions, so far as are known, invariably are found together with certain other conditions; and (2) a law is probabilistic if it affirms that, on the average, a stated fraction of cases displaying a given condition will display a certain other condition as well. In either case, a law may be valid even though it obtains only under special circumstances or as a convenient approximation. Moreover, a law of nature has no logical necessity; rather, it rests directly or indirectly upon the evidence of experience
Physical component	An atomic-level element of the system
Environment	All the other subsets of the universe apart from the system constitute the environment. The system boundary demarcates the system from its environment
Boundary	The border that separates the system and the environment
Physical variable	A model of a property of the system or of the environment characterized by a symbol and a value or a set of values that constitute the instantaneous instance of the model
Interaction	It is the communication between a system and its environment with each other to reach equilibrium. The equilibrium here refers to a balance in the properties of the system and environment. A system and its environment try to attain equilibrium because it is the most stable condition. It is governed by effects.
Interface	A surface lying between two portions of matter or space, and forming their common boundary
State	A property of the system (or its environment) that is involved in an interaction
Organ	A set of properties and conditions of the system and its environment required for an interaction between them
Effect	A Principle of Nature that underlies and governs an interaction
Input	A physical variable that crosses the system boundary and is essential for an interaction between the system and its environment
Physical phenomenon	An interaction between the system and its environment
Action	An abstract description or high-level interpretation of an interaction between the system and its environment
Parts	A set of physical components and interfaces that constitute the system of interest and its environment

Table A2. DANE complete ontology.

Cause	That which produces an effect; that which gives rise to any action, phenomenon, or condition
Condition	Something demanded or required as a prerequisite to the granting or performance of something else; a provision, a stipulation
Device	An object or a piece of equipment that has benne designed to do a particular job
Fluid	Having the property of flowing; consisting of particles that move freely among themselves, so as to give way before the slightest pressure (a general term including both gaseous and liquid substances)
Force	Strength, power
Purpose	That which a system sets out to do or attain; an object in view; a determined intention or aim
Universe	All existing matter and space considered as a whole
Causal	A thing implying a cause
Connections	Connections are partitioned into categories based on the way in which force is transferred between the corresponding components
Connecting point	Portion of an element through which it interacts with other elements
Properties	An attribute, characteristic, or quality of the universe and/or of any of its parts
Substance	Fluids and forces (see components)
System	A subset of the universe that is under consideration.
Element	An Element is either a physical Component or a Substance
Environment	All the other subsets of the universe apart from the system constitute the environment. The system boundary demarcates the system from its environment
States	A set of properties of the system (or its environment) that is involved in an interaction
Components	Components are Elements that can be connected with other Components. They should be distinguished from Substances, which are used to model fluids and forces
Postconditions	A condition that is fulfilled after other things happened
Preconditions	A prior condition or state. Also, a condition or term that must be fulfilled before other things can happen or be done; a preliminary stipulation, a prerequisite
Structure Model	A Structure Model is merely one or more Elements and the Connections among them
Transition	Transitions are directed binary associations between States. Each Transition might have a number of Causal Explanations motivating the change of State
Variables	A value or set of values that can be associated and used to describe a property of the system or of the environment
State transition	Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behavior
State variables	Variables used to define a state
Stimuli	The final constituent of an SBF Model describes the environmental Stimuli that can affect its Behavior. A stimulus may have an associated typed value, describing its amplitude.
Functional abstraction	The specification of a component includes its functional abstractions, where a component can have multiple such functions

(*Continued*)

Behavior	A behavior is represented as a sequence of states and transitions between them. The states and the transitions are represented as state and transition schemas, respectively. The states in a behavior specify the evolution in the values of the parameters of substances and/or components. Continuous state variables are discretized, and temporal ordering is subsumed by causal ordering. Each state transition in a behavior is annotated by the causes for the transition. Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behavior.
Function	A function is represented as a schema that specifies its preconditions and its postconditions. The function schema contains a reference to the behavior that accomplishes the function. This schema also may specify conditions under which the specified behavior achieves the given function (e.g., an external stimulus). Functions in SBF describe the role that an Element plays in the overall operation of a device. They express the purpose or goal of the Element, whereas the Behavior describes how the purpose is accomplished
Structure	In SBF models, structure is represented in terms of components, the substances contained in the components, and connections among the components. The specification of a component includes its functional abstractions, where a component can have multiple functions. The specification of a substance includes its properties. Substances can be abstract, e.g., angular momentum