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CAUSAL MODELS FOR BIO-INSPIRED DESIGN: A COMPARISON

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1. Introduction

Bio-Inspired Design (BID), i.e. Nature as a source of inspiration for inventive design and problem solving, is receiving a growing interest by the scientific community. Several motivations underlie this trend; among the others, the strong belief that bio-inspired engineering products and processes are characterized by higher performances and reduced environmental impact.
While several research efforts have been dedicated since decades to the study and development of biomimetic solutions both for industrial and scientific purposes, just recently, more systematic investigations about the design process for guiding a bio-inspired approach emerged.
Several BID causal models have enriched the engineering design literature of the last decade, but still none of them has been adopted as a common reference by the scientific community to further build on it 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 et al. and the DANE model by Vattan et al. (more detailed references are provided in the next sections). 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.
This paper aims at contributing to this debate with the ultimate goal to bring some suggestions for the construction of a reference model for BID. More precisely, the lack of an established model for Bio-Inspired Design might be faced with different approaches: we might propose a totally new model exploiting the lessons learned from the existing literature; we might choose one of the existing models and build on it the missing features; finally, we might aim at integrating several selected existing BID models to gain a synergic benefit through their combination. Despite its intrinsic higher complexity, we lately decided to opt for the latter approach, since it is expected to have the higher chances of acceptance by the scientific community.
According to this objective, the specific research question addressed by this paper is a check of compatibility between the selected BID models with the perspective of proposing an integrated view on them. Therefore, after a short survey on the main characteristics of SAPPhIRE and DANE, the third section shows with a practical example the complementary nature of these models. Section 4 presents an original methodological approach for their comparative analysis and then the most relevant outcomes of this study and a constructive discussion about the planned further developments follow.

2. State of art: BID languages and techniques

The design of products by means of a biomimetic approach is largely debated in scientific and technical literature. On the other hand, very often the BID process is initiated by fortuitous

“coincidences” or by designers’ personal interests. The research effort in this field is now mainly aimed at making designers more familiar with this approach. In particular, big efforts are devoted to transfer the biological knowledge into the engineering field.
The great majority of the strategies conceived and developed to transfer knowledge from the biological to the engineering field can be grouped in three main categories.
A first cluster aims at integrating the biological knowledge in an existing design method. For example, Julian F. Vincent and his group aimed at achieving a “systematic technology transfer from biology to engineering” [Vincent and Mann 2002]. The main strategy they proposed was to redefine the TRIZ approach on the basis of Nature. In order to achieve this goal, they developed a database of biological effects, which can be used in engineering design process as a source of engineering principles or practical solutions.
The second approach exploits the potential of computational linguistics for the analysis of natural language, so as to reduce the huge preliminary translation work necessary to map the natural science knowledge into an engineering science “language”. For example, Chiu and Shu [Chiu and Shu 2007] developed a “method to systematically bridge the disparate biology and engineering domains by using natural language analysis”. Their main aim is not to categorize solutions for specific problems, but to “algorithmically generate a non-obvious keyword provided by a domain expert as one of many other non-obvious but relevant keywords”.
A latter approach consists in developing a functional representation of biological phenomena and in storing this information in a database; the key idea is to “transform” the knowledge before it reaches engineers.
Among many others, this strategy has been followed by Chakrabarti and his research group, who developed “a generic model for representing causality of natural and artificial systems” to “structure information in a database of systems from both domains” [Chakrabarti et al. 2005].
Starting from the existing models of functional reasoning, including the Function-Behaviour-Structure framework, they developed a “functional/behavioural representation” for natural and artificial systems. This language has been named SAPPhIRE, which is the acronym of the constituent components of the model used to describe a biological solution. The authors of SAPPhIRE continuously evolved this model as documented by several papers, by modifying and improving the definitions of the model components. In addition, they introduced and deepened the definitions of the other items required to represent and build the system model. The definitions of the main components of their model can be found in [Chakrabarti et al. 2005], and are summarized in Table 1. In the next sections, the latest available definitions will be assumed as starting reference, even if the previous definitions have been taken into account to better understand their meaning.
More recently, Vattam et al. presented “an interactive knowledge-based design environment called DANE” (**D**esign by **A**nalogy to **N**ature **E**ngine), which “provides access to a design case library containing **S**tructure-**B**ehaviour-**F**unction (SBF) models of biological and engineering systems” [Vattam et al. 2010]. The definitions of the main components of their model can be found in a previous paper [Goel et al. 2009], and are summarized in Table 2.

Table 1. Main definitions of the SAPPhIRE model

State: A property of the system (or its environment) that is involved in an interaction.
Action: An abstract description or high-level interpretation of an interaction between the system and its environment
Part: A set of physical components and interfaces that constitute the system of interest and its environment
Phenomenon: 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
Organ: A set of properties and conditions of the system and its environment required for an interaction between them

Table 2. Main definitions of the DANE (design by analogy to nature engine) model

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 also may specify conditions under which the specified behavior achieves the given function (e.g., an external stimulus).
Behaviour: 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.

3. Showing DANE and SAPPhIRE complementarity trhough a practical example

With the aim of clarifying the motivation of the following analysis of the selected models, this section presents an example of bio-inspired solution selected from literature beyond the papers on DANE and SAPPhIRE. Both the natural source of inspiration and the technical system produced through this source of inspiration have been modelled with the two BID approaches. As a result, it is possible to appreciate the complementary characteristics of the information they can represent.

The selected case study is the micro-fluidic device, which is capable to "separate leukocytes from whole blood" [Shevkoplyas et al. 2005] (Figure 1.a). This device relies on natural phenomena known as plasma skimming and leukocyte margination. In fact, it closely imitates the blood micro-circulation and consists in a "network of rectangular micro-channels designed to enhance the lateral migration of leukocytes and their subsequent extraction from the erythrocyte-depleted region near sidewalls". This device guarantees a continuous flow, provided by a small pressure gradient that supports the flow of blood.

Since erythrocytes are smaller and more deformable with respect to leukocytes, they "tend to flow at the centre of blood vessels, leaving a plasma-rich zone adjacent to the vessel wall; they also flow faster than leukocytes". This behaviour "encourages collisions" between leukocytes and erythrocytes, which result in an enrichment in leukocyte of the zone close to the vessel wall. A portion of the blood richer in leukocyte can be then extracted from the main flow, forcing the blood to flow trough an asymmetric bifurcation. The whole process can be seen as a repetition of two main phases: firstly, leukocyte naturally migrates towards the wall; secondly, the layers near the wall are extracted from the main flow by means of asymmetric bifurcations.

Figure 1.b shows the SAPPhIRE model of the leukocyte lateral migration phenomenon. A uniform distribution of leukocytes and erythrocytes ("input") in the blood ("part") flowing in a micro-channel ("part") activate collisions ("physical phenomenon") between leukocyte and erythrocyte, thanks to plasma skimming ("physical effects"). This results in a change of leukocyte distribution ("state"). The complete process is known as leukocyte margination.

Figure 2 shows the three main parts of the DANE model. In particular, Figure 2 (b) shows the "Behaviour" model of the whole process of the device. The two subsequent phases as well as their correlation can be easily identified. The representation of a two phases process in SAPPhIRE requires at least two instances of the model (one for each phase), while in DANE it is possible to add as many states as needed. Therefore, the two phases can be represented in a unique instance of the model.

Comparing these two representations, the SAPPhIRE approach appears to be more suitable to highlight the causal relations in the system. Furthermore, it is somehow more flexible, allowing the user to represent information at a higher abstraction level. On the other hand, the DANE schema embeds an explicit representation of the sequence of state changes that occurs in the overall process, highlighting the physical parameters involved in each of them. On the contrary, the instances of the SAPPhIRE schema, which represent different phases of the same process, cannot be directly and explicitly correlated. In the SAPPhIRE model, "State" and "Action" are only connected to the "Input" of the same diagram (i.e. the same phase of the process).

Let's consider the blood flow generation because of a pressure gradient (Bernoulli Effect) as an example. The pressure gradient is required to generate the flow, but it is generated by an external device, and therefore it cannot be interpreted as a consequence of any action or of any physical phenomenon of the process. A similar situation occurs in the den of prairie dog [Sartori et al. 2010], where the pressure gradient ("Input") is generated by the wind (external phenomenon) and not by den ventilation ("Action"). Finally, in SAPPhIRE, system and environment parts are listed altogether in a unique field, which is connected to the "Organ" field only. Besides, the DANE model includes a structure representation that allows to explicitly describe the structural relationships among the parts.

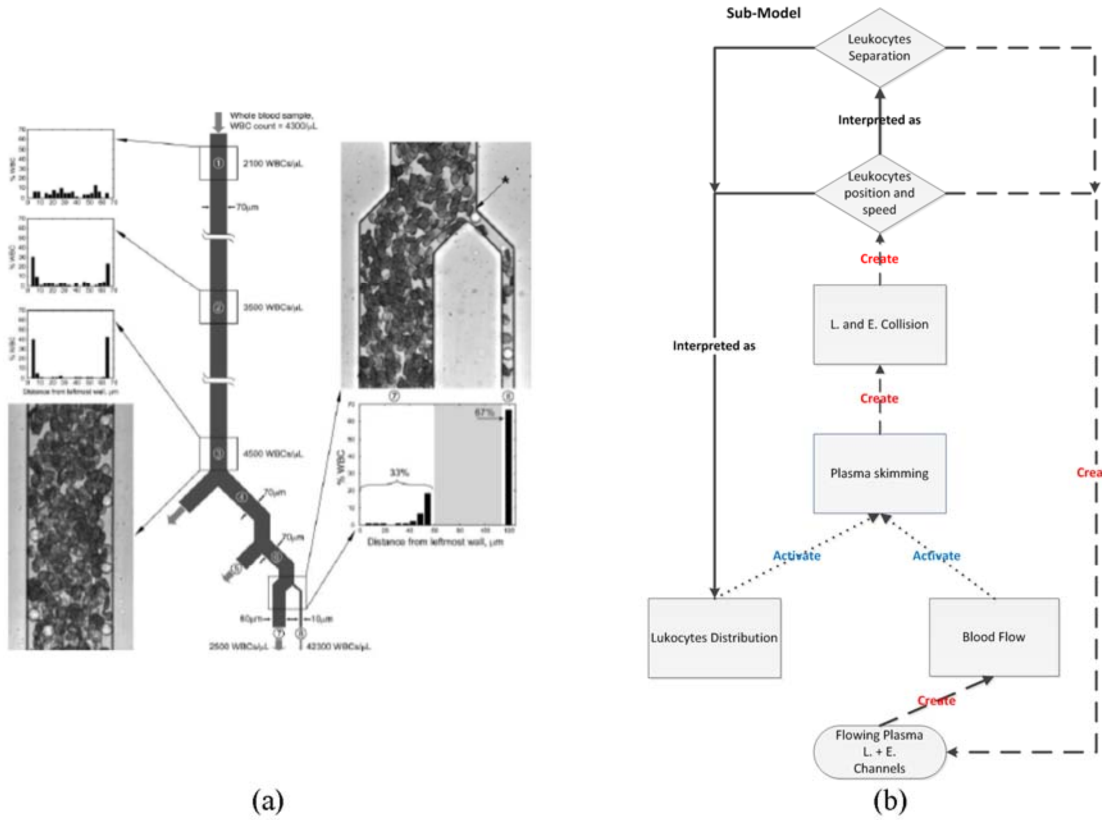

Figure 1. (a) Micro-fluidic device schema; (b) SAPPhiRE model of leukocytes separation; (c) SAPPHiRE model of the whole system

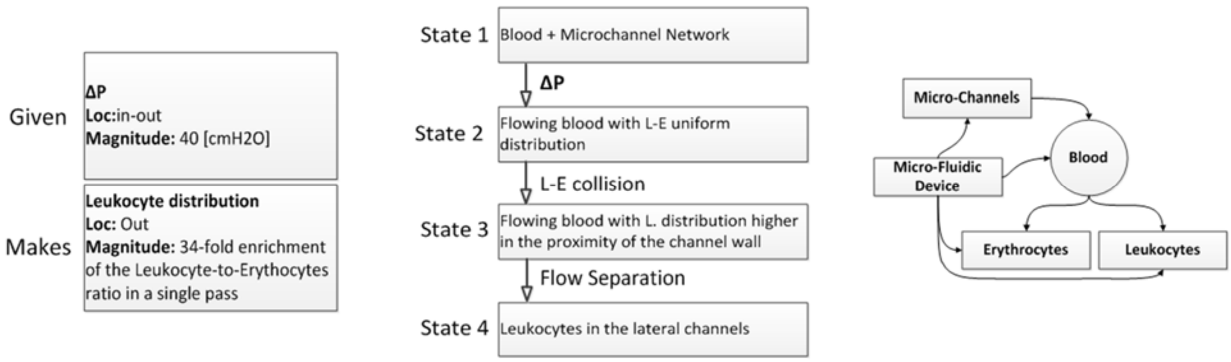

Figure 2. Function (a), behaviour (b) and structure (c) models according to DANE

A first intuitive conclusion can be drawn: the two BID models more debated in scientific literature are devoted to the representation of complementary information. It is therefore useful to investigate with a formal study their degree of overlap, as well as the existence of contradictory characteristics, which might hinder their integration.

4. Models comparison: Methodological approach

The analysis carried out on the DANE and SAPPhIRE models consists of three main steps. First, an ontology of the terms used for defining each model has been built on the basis of their constituent components and further related items. Secondly, all the items of the model ontology have been hierarchically structured through a network of semantic oriented links (i.e. A→ B should be intended as A is used to define B). The output of such a step is a conceptual map representing the model components and their semantic dependencies. Thirdly, the conceptual maps of the two models and their informational content have been compared, according to the ultimate objective of this study, i.e. to analyze the differences between the most developed BID frameworks and check their integrability.

This section presents the main strategies and techniques adopted in this analysis, as well as its underlying criteria. As a first step, the semantically significant terms have been extracted from the definitions of the main components of the two models. After that, their definitions have been searched within all the related papers of the same authors. If no definition is available, a semantically related definition of the term has been sought in the Oxford English Dictionary (assuming that one of the common definitions can be adopted, if the authors does not supply a specific definition). In those cases such that none of the OED definitions is suitable for the scope of this study, due to a semantic gap between the model and the typical meaning of the terms, a new definition has been formulated, possibly taking inspiration by an equivalent term of the other model. The same procedure has then been reiterated with the obtained definitions, until a "basic" level has been reached. This level is characterized by general terms, the meaning of which does not need any further explanation. As an example, let us consider the definition of Organ in SAPPhIRE: "a set of <u>properties</u> and <u>conditions</u> of the <u>system</u> and its <u>environment</u> required for an <u>interaction</u> between them" [Sartori et al. 2010]. First, the terms that semantically characterize the term Organ have been highlighted. As a second step, their definitions have been searched in the related papers. For example, a definition of "system" appears in SAPPhIRE 2009: "A subset of the universe that is under consideration", but no explicit definition appears for the term "property"; hence it was searched in the OED, which suggests the following definition: "An attribute, characteristic, or quality of the universe". Both these definitions contain terms that, in our opinion, do not need any further specification, and hence belong to the basic level.

4.1 Model features

For the sake of brevity, in the next sections the following expressions will be used:

- Primary: components that form the original set of terms of the model;
- Secondary: further items needed to define primary components or other secondary ones.

4.1.1 SAPPhIRE – DANE: Features and definitions

A different number of primary components characterize the two models:

- SAPPhIRE: 7 (i.e. State change, Action, Parts, Phenomenon, Input, oRgans, Effect)
- DANE: 3 (i.e. Function, Behaviour, Structure)

Starting from these components, the terms and the concepts used to define in an unambiguous way each term of the model has been analyzed. As explained above, the analysis has been stopped when a component definition is constituted only by basic and common sense terms.

The overall number of secondary components is 13 in SAPPhIRE and 27 in DANE.

To the whole set of primary and secondary components of each model has been assigned an explicit definition, classified as follows and marked with different colours (and backgrounds) in the conceptual maps described in the next section:

- Definitions from the original model literature (Yellow Primary /Brown Secondary)
- Oxford English Dictionary definitions (Blue)
- Further definitions (proposed in this paper) (Green)

The secondary terms explicitly defined are (in the following lists, the definitions shared by the two models are in italic):

- SAPPhIRE: System, Environment, Interaction

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

The two definitions of state (secondary in DANE, but primary in SAPPhIRE) show a good agreement, and therefore it has been considered a term common to both models.

As expected, the Oxford English Dictionary (OED) definitions are suitable to define the great majority of the secondary terms not explicitly defined in the two models. In particular, the OED definitions have been adopted for the following terms:

- 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 considered equivalent for both models, since the explicit SAPPhIRE definition is practically identical to the OED definition.

This solution was not practicable for other secondary terms (listed in Table 3), the specific connotation of which has required the conception of specific definitions, which have been developed on the basis of the connections and of the use of these terms within the two models.

Table 3. Author's proposal definitions

Terms	Definition	Model
Physical component	An atomic level element of the system	**SAPPhIRE**
Boundary	The border which 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 which constitute the instantaneous instance of the model	**SAPPhIRE**
State variable	Variables used to define a state	**DANE**
Connecting Point	Portion of an element trough which it interacts with other elements	**DANE**
System	A subset of the universe which is under consideration*	**DANE**
Postcondition	A condition that is fulfilled after something happened	**DANE**

*The definition of the term system proposed for DANE is the definition of this term adopted in SAPPhIRE.

4.1.2 Conceptual models of SAPPhIRE and DANE

A conceptual map has been developed to represent the ontology of each model (Figure 3, SAPPhIRE; Figure 4, DANE): each box contains a term (primary or secondary) and a colour (and background) code identifies its source, as defined in the previous paragraph. The semantic dependencies between the ontology items allow to hierarchically classify the terms in different levels: level zero is constituted by basic and common sense terms; a term is assigned to level i-th, if its definition is based at least on a (i-1)-th level term. The resulting hierarchies of the two models count 6 levels in SAPPhIRE and 8 levels in DANE.

The conceptual maps highlight also the distance of a semantic dependency in terms of hierarchical levels: an i-th level term defined by means of a j-th term is characterized by a (i-j) level link. The DANE ontology presents recursive definitions and loops: as for instance, the term "stimuli" is not explicitly defined, but through an implicit description: "The final constituent of an SBF Model describes the environmental Stimuli that can affect its Behaviour. A Stimulus may have an associated Typed Value, describing its amplitude" [Goel et al. 2009]. Besides, the term "component" is defined by referring to "elements" and "connections", while the definition of the latter has a reference to "components". The conceptual map in Figure 2 highlights this anomaly through dashed lines.

Eventually, it is possible to extract further information from the conceptual map, i.e. the number of links needed to define each term or, in other terms, the degree of connectivity of the model.

The resulting comparison matrix is made up of 20 rows (7 primary components of the SAPPhIRE model plus 13 secondary item) and 30 columns (3 primary components of the DANE model plus 27 secondary item). A cell of this matrix takes value "YES", if the definitions of the related terms share the same meaning; "NO", if the two terms are not semantically related; finally, a "PARTIAL" value is assigned when the definitions of the two terms are partially overlapping. In the latter case a set operator clarifies if the definition of one term of the model includes one or more terms of the other model. It is worth noting that no directly conflicting definitions have been observed.

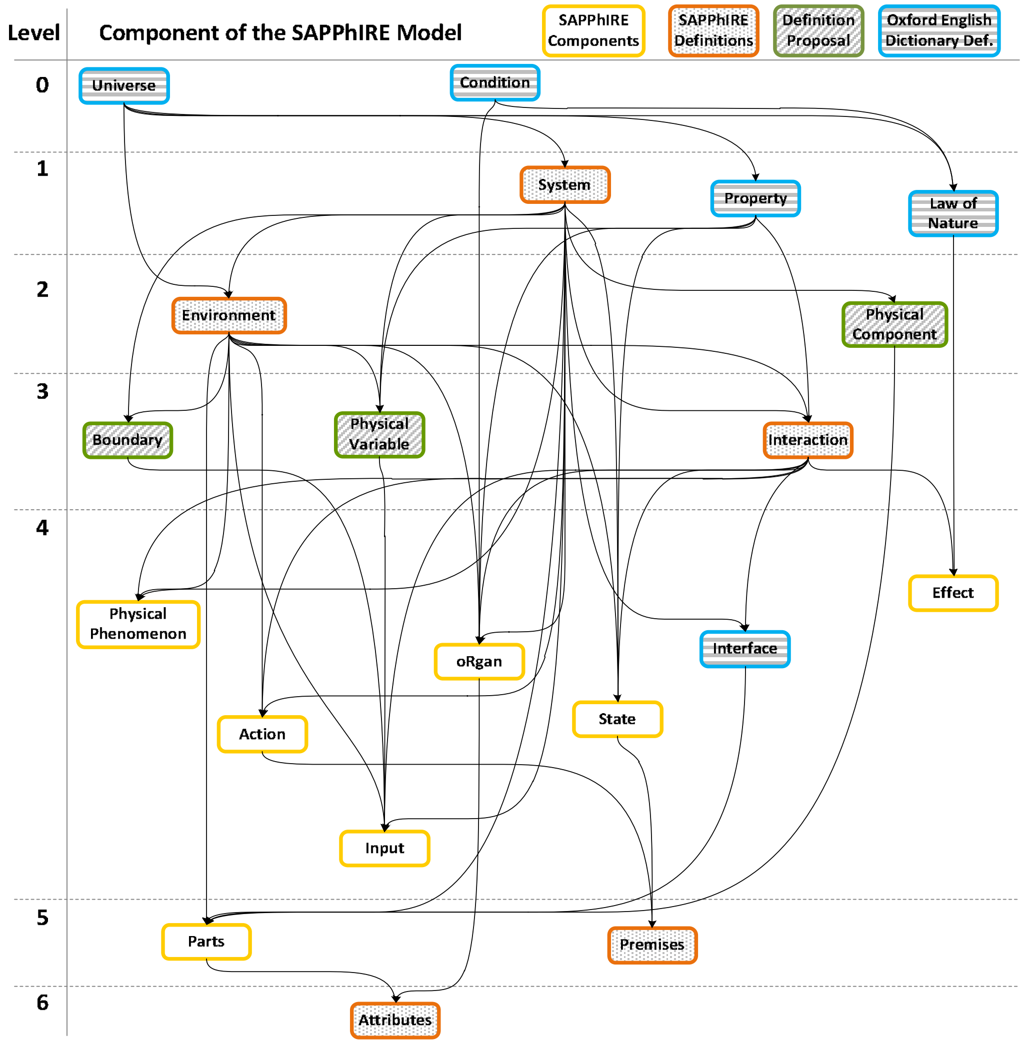

Figure 3. SAPPhIRE conceptual map

4.2 Comparison criteria

Beyond the numerical comparison in terms of components and connectivity, the models have been more deeply investigated to check their potential integrability: each item of the SAPPhIRE ontology has been compared with the terms of the DANE ontology and vice versa, looking for overlapping and conflicting definitions.

5. Comparison's results

This section summarizes the outcomes of the analyses conducted on the basis of the criteria described in the previous chapter, while the conclusions that can be drawn from these figures are discussed in the next section.

Initially, the models ontologies are compared in terms of sources of the definitions of their terms, as depicted in Table 3. A further comparison relates the distribution of the terms in the hierarchical levels defined in section 4.1.2 (Table 4). In order to estimate the overlap between the terms of the two models, a two-stages comparison has been carried out.

First, the terms used in both models have been identified. As expected, the definition of each of these terms is appropriate for both models. In the second phase, the meaning of the other terms (i.e. the terms used in one model only) has been compared.

As a result of this analysis, only partial correspondences (see section 4.2) have been identified. This means that the same term is never used with two different meanings in the two models and that the same idea is never expressed by two different terms in the two models. Tab. 5 summarizes these results: the column "Unique Name" shows the number of terms used in only one model, while the column "Unique Name and Definition" shows the number of terms that do not have any (partial or full) correspondence.

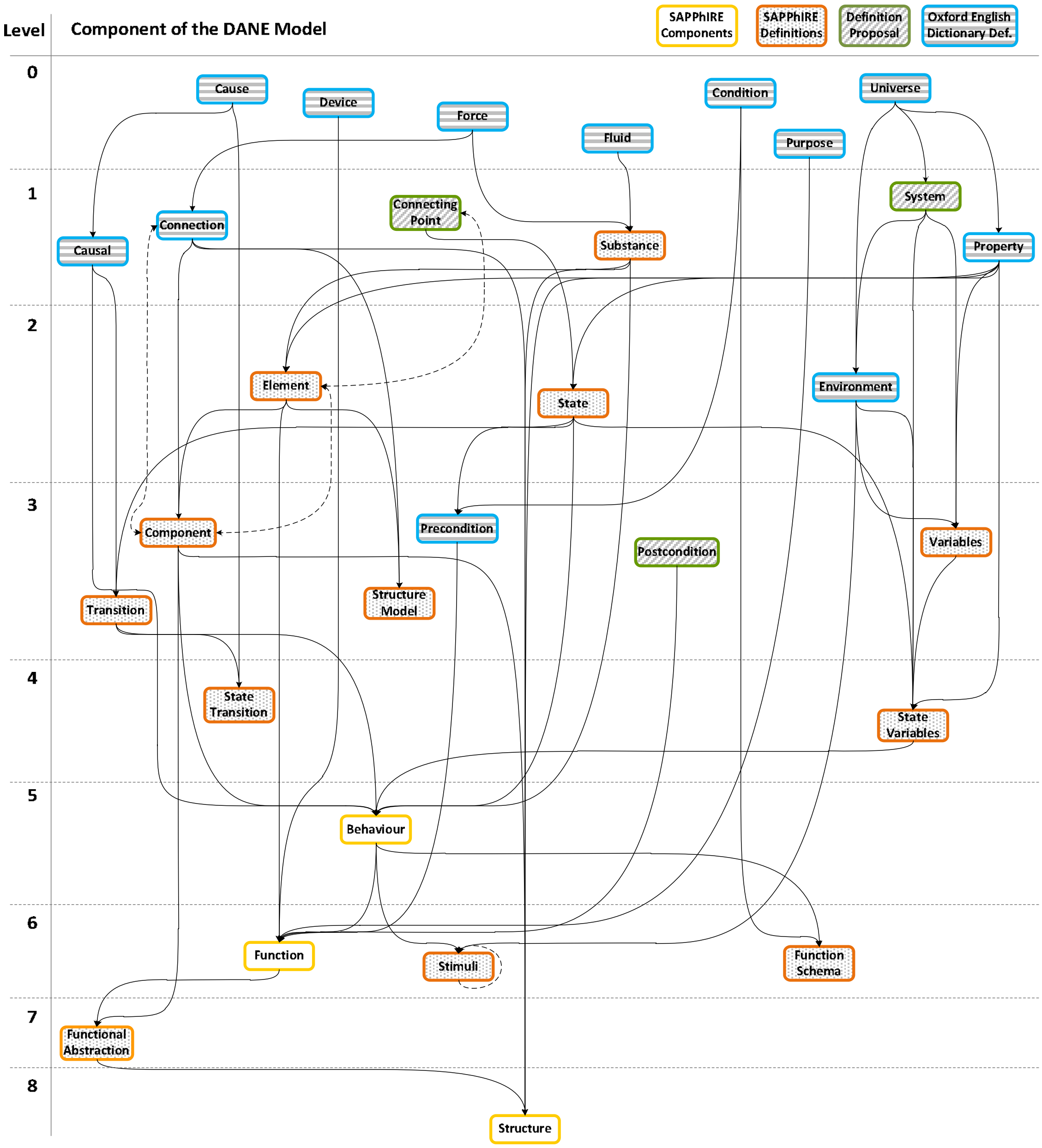

Figure 4. DANE conceptual map

Table 4. Source of the definitions adopted to build the ontology of the BID models

Definitions source	SAPPhIRE		DANE	
Definitions from the original model literature	12	60,0%	14	46,7%
Oxford English Dictionary	4	20,0%	11	36,7%
Further definitions	4	20,0%	5*	16,7%

* one of these further definitions, namely environment, has been assigned equivalent to environment of the SAPPhIRE ontology, due to its suitability within the DANE framework and according to the perspective to integrate the models.

Table 5. Comparison of BID models hierarchies

Level	SAPPhIRE		DANE	
0	2	10,0%	8	26,7%
1	3	15,0%	6	20,0%
2	2	10,0%	3	10,0%
3	3	15,0%	5	16,7%
4	7	35,0%	2	6,7%
5	2	10,0%	2	6,7%
6	1	5,0%	2	6,7%
7	-	-	1	3,3%
8	-	-	1	3,3%

Table 6. Unique terms distribution

	Unique Name		Unique Name and Definition	
DANE	24	80,0%	13	54%
SAPPhIRE	14	70,0%	5	36%

6. Discussion

In this section, the noteworthy differences between the two analyzed models are highlighted. On the basis of these differences, a first and rough attempt to link them to the main purposes of DANE and SAPPhIRE will be presented and discussed. From a direct comparison between the two conceptual maps depicted in Figure 3 and in Figure 4, it can be noticed that in the SAPPhIRE model:

- There are less levels and its elements have less interconnections;
- There is no recursive definition;
- There are more primary elements: this result seems consistent with one of the main aims of the SAPPhIRE model, that is to link Function, Behaviour and Structure to each other;
- A great part of the semantically significant terms are explicitly defined;
- The basic level (No. 0) contains fewer elements: this result can be explained observing that some basic terms (e.g. “force”) are not explicitly included in the SAPPhIRE lexicon, even if they are likely to be used in the descriptions of the SAPPhIRE primary terms.

The comparison of the primary terms reveals that only few and partial correspondences exist. This result seems to be somehow consistent with the brief comparison between SAPPhIRE and a generic FBS model in [Chakrabartiat et al. 2005]: in section 5.1 the authors highlight the elements that are the core of the behaviour of a system, and explicitly state that “Structure is described by the *elements* and *interfaces* of which the system and its immediate, interacting environment are made”. In order to find a correspondence of this “definition” within the DANE model, the terms *element* and *interface* have been analyzed in more detail. Since, they are not explicitly defined in the SAPPhIRE model, other definitions have been sought. The term *interface* does not resemble any term of the model. Hence, a definition extracted from the OED has been adopted. On the other hand, on the basis of its usual meaning, *element* is somehow related to the *physical component* term of the SAPPhIRE model. According to these considerations and based on the latest definition of *Parts* (see Table 1), a partial correspondence between *Structure* and *Parts* has been acknowledged. Nevertheless, a partial correspondence between *Structure* and *Organ* is also present, since an *Organ* describes all the properties and the conditions of the system and its environment that are required for an interaction between them. It is also worth nothing that the former definition of *Organ* explicitly refers to the structural aspect. Analysing *Function* and *Behaviour* meaning in DANE, only a partial correspondence between *Behaviour* (DANE) and *Physical phenomenon* (SAPPhIRE) has been recognized: it seems that a *Physical phenomenon* (“an interaction between the system and its environment”) can be used to describe the behaviour of the system.

Comparing the secondary terms, it can be easily observed that many of them are practically identical: this is not due to a conformity of the two models, but to the fact that practically none of the terms of the lower levels (0, 1, 2) is explicitly and independently defined in both models. As a result, many of these definitions have been proposed by the authors or extracted from the OED: obviously, the result is a good correspondence, also because the authors’ aim is to build a semantically harmonized lexicon that can be used to build both models.

While analyzing the terms that belong to only one of the two models, it has been noticed that only a half of them 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. This consideration somehow complies with the typical application of the two models, as to say what their authors have conceived the two models for. SAPPhIRE seems to be more suitable to describe the system as a whole and its interaction with the environment (e.g. the prairie dog den example in [Sartori et al. 2010]), without describing in detail the internal "behaviour" of the system. On the other hand, DANE seems to be a model conceived to describe the internal features of a system that is accomplishing a function and its evolution (e.g. the model of a flamingo's filter feeding apparatus in [Vattamat et al. 2010]).

7. Conclusions and future work

Among the BID causal models available in literature, DANE and SAPPhIRE certainly share the greatest attention for both the consistency and the regularity of their development over the years. Besides, these models cannot be considered as alternative frameworks, since they are characterized by substantially complementary characteristics. With the ultimate goal of building an integrated model suitable for supporting any BID activities, the authors of the present paper have proposed a systematic comparison of DANE and SAPPhIRE ontologies, which demonstrated that these models present some semantic gaps, but no conflicting definitions or relationships. Therefore, it is worth building a common lexicon, mostly based on standard definitions selected from the Oxford English Dictionary, and completed with custom definitions proposed in this paper, that can be used as the founding brick for the construction of an integrated framework. The next step of this research activity will then consist in a more complete definition of this common basis, in order to gain the capability to describe a generic biological system as a whole, with the holistic perspective of the SAPPhIRE representation, as well as its internal structure and behaviour, as for the DANE modelling approach.

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