Models of knowledge for Virtual Scientific Experiments

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Abstract

One of the most advanced tools for e-learning is the Virtual Scientific Experiment (VSE). Its value for theoretical research and practical employment relies (a) on the chance it provides to integrate traditional conceptual contents with no explicit and no declarative forms of teaching, (b) on its massively exploitation of modern ICT instruments, and, finally, (c) on its capacity to instantiate extremely interactive and constructive learning models.

In this paper we provide a characterization of VSE that takes into account the relation between the properties of the formative domain (the system of knowledge the student should learn) and those of the formative object (the specific VSE).The result is a model of knowledge based on the concept of action as a connection between formative states.

Studying topological properties of the representations and dynamics of VSEs, we identify three basic structures: convergent, multi-convergent, and by propagation. Each of these structures has specific properties which should be considered during the design and assessment of learning processes by VSE. Firstly, we provide the theoretical analysis by the means of which we build the single model: we show how to formalize system actions and configuration and we describe how to apply this analysis to the learning dynamics which takes place as the VSE is being used. Secondly, we introduce a case study for each model in order to clarify empirically how they work.

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1. Introduction: Virtual Scientific Experiment

Virtual Scientific Experiments (henceforth, VSE) are tools for education and learning that derive from the new technological and theoretical developments of simulation theory and e-learning virtual environments.

Using VSEs, students can intervene on a set of variables of an experimental system (constructed by simulation) in order to (a) test their informal or implicit knowledge of that system, (b) independently build «new» knowledge about that system, (c) compare the results of (a) and (b) with the theoretical hypotheses (the knowledge the designer wants to grant through the VSE). VSE designers generally study how students can reach the target the teachers have decided by passing from a prerequisite to a self-constructed knowledge.

VSEs design and implementation can be specified by considering: the set of relations that agents and systems involved in the learning process must bring about, the targets they have to reach and the theoretical context in which the virtual environments and simulations are devised. Thus, VSEs can be considered as an interface between the teacher and the knowledge to be obtained, including:

1. *formative target,* i.e. the specific scientific knowledge the teacher has defined must be aquired by the students after the learning process – e.g. the second law of Newton, the laws of oscillatory motion, the relationship between supply and demand etc.;
2. *formative object,* i.e. the specific experimental system that manipulated via simulation by the student allows to reach formative target – e.g. inclined plane, pendulum, a specific economic system;
3. *virtual experimental environment,* i.e. the interactive simulation of scientific experiment which incorporates the knowledge of formative target – e.g. how to manipulate the variables of the simulation, how to organize the interactive space on the display etc.;
4. *some intermediate steps (sub-targets),* which perform a twofold function:
   a) they lead the teacher in the VSE construction, since they represent the different phases the student has to pass by in the learning process;
   b) a verification for the student of the improvements thanks to formative target, represented by questions and constraining interventions on the possible manipulation made on the simulated system.

These intermediate steps can be considered as a series of preliminary abstractions the student affords approaching the formative target.

When selecting the objects and processes that characterize the virtual environment of the experiment, designers have to take into account also:

a) *a theoretical paradigm,* i.e. a series of pedagogical conditions the VSE must fulfil (see Brosseau, 1986; Jonassen, 1994; Wenger, 1998);

b) *a specific model of knowledge,* which depends on the formative object (to simulate) and the formative target (to be reached);
c) *a model of learning,* i.e. a series of structures which the student's knowledge has to adapt to;
d) *some constraints* due to the specific simulation program and to the e-learning platform where the VSE is to be implemented.

In this paper we provide a model that can represent all the states of knowledge and the operations which are needed to connect these states, in order to have a coherent framework to design and implement VSE.

2. Models of knowledge

Traditionally, the design of e-learning courses relies on a series of conceptual tools as Learning Objects (LO), Metadata (MD), Ontologies (ONT). These tools organize the learning content formalizing it in such a way that its implementation becomes increasingly easier.

Thus, if the content is correctly formalized by using LO, MT and ONT, it is even possible to implement it automatically, as some recent e-learning platforms allow.

Generally, the model of knowledge for a didactic unit is made up of three levels of abstraction (see fig. 1):

1. the lower level is determined by Learning Objects, elementary didactic modules that are used for the formative process;
2. the second level is determined by Metadata, its role is to formally specify LO with a standard set of attributes;
3. the third level (the upper one) is represented by Ontologies which are a means to structure the concepts that orientate the constitution of an LO.

Ontology links concepts following two possible kinds of relations:

1. *relation B (belongs to).* It constitutes the hierarchy of concepts. In order to learn a concept it is necessary and sufficient to learn every related concept;
2. *relation R (requires).* It implements the idea that a concept is a requisite for another concept. In order to learn a concept it is necessary to preliminarily learn every related concept.

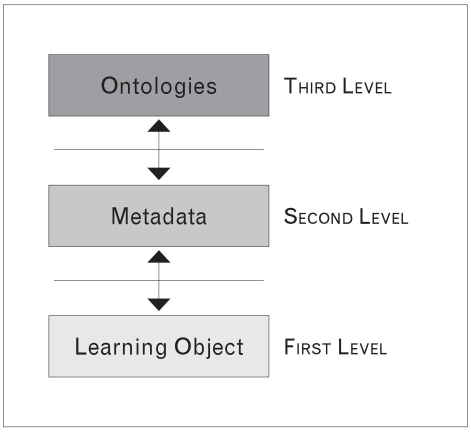

Figure 1 Three levels.

For example, let's say the didactic unit is about mathematical analysis. In order to learn it, the following concepts must be understood: limits, derivative, integrals, series (relation B). Before the learning series, the knowledge of integrals is required, before the integrals the derivatives and, finally, before the derivatives the limits (see fig. 2).

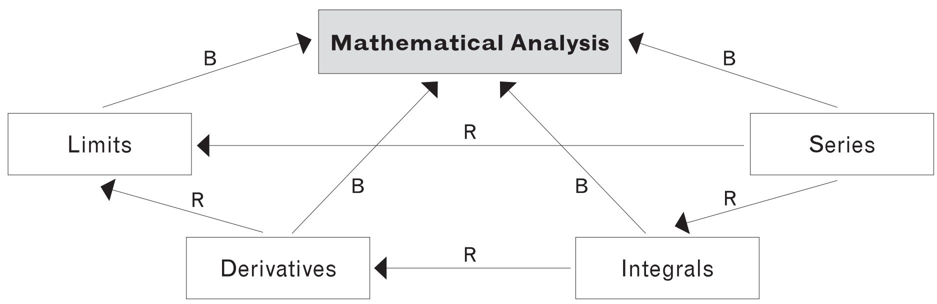

Figure 2 A possible ontology for mathematical analysis.

At the Ontology level, an e-learning course design consists in the definition of concepts and their mutual relations. Successively, an LO is associated to each concept. LOs represent concepts with different modalities: a hyper-text, a multimedia video, a VSE etc..

Thus VSEs are LOs. In this work we explain how knowledge can be represented within a VSE. We claim that VSEs are peculiar LOs in which the knowledge is not explicitly declared but it depends on a series of successive abstractions. A student reaches the formative target (the concept to be learned) through such abstractions by interacting with the virtual experiment.

This distinctiveness depends on the learning model underpinning the constitution of VSEs. What a teacher/designer expects from the student who exploits a VSE is that he/she can autonomously form his/her knowledge self-constructing the path to the formative target (which should have been given to him/her explicitly at the beginning of the VSE). Using ontologies to formalize VSEs, the path the student builds up to the formative target is out of the teacher/designer's forecasts.

How can a VSE be realized when it seems impossible to imagine which path the student's learning process will take to the formative target?

We introduce the student's learning *actions* to the formative target, evaluating and representing them with graphs. Graphs are a powerful mathematical technique which allows to formalize a large cluster of problems. Before introducing our models, we briefly provide some basic concepts of graph theory.

A graph is a set of objects called vertices (or nodes) connected by links called edges (or arcs) which can be directed (assigned a direction). A graph is designed as a set of dots (the vertices) connected by lines (the edges).

Our idea is to find some structures, which — equipped with states (nodes) and actions (edges) that lead to that state — can match the representation of the student's learning states. When building this model, we need to describe the knowledge domain in terms of actions, modifying that domain by state transitions. We propose three kinds of structures: convergent, multi-convergent and by propagation.

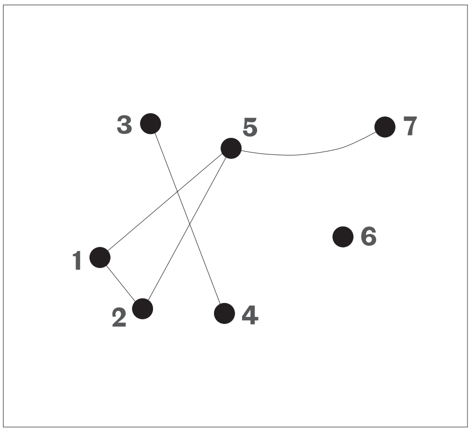

Figure 3 A simple graph.

3. Three structures for VSEs

The structures we propose can be specifically identified only by considering the formative target.

Convergent models are useful for those VSEs in which the formative target is, for example, a physical law, where the knowledge is determined by a single solution (a single final state). Multi-convergent models should be applied when all the intermediate steps refine and converge to diverse final states. In this case, the student can reach diverse didactic solutions by manipulating the simulative environment in a very personalised way — it is possible to use such structures when it is necessary to learn how different solutions can be applied to a certain problem, like in mechanical or civil engineering. The model by propagation depends on how information is distributed over the graph. We are not interested in the student's learning path, but rather in determining how the student can learn the dynamics of a certain system by observing the consequences of his/her manipulation of the system and resulting performance. This kind of model is useful when concepts are clearly defined and we are interested in studying the mutual relation of the nodes by observing each possible change in one of their values as other values change (or remain constant). With this model it is possible to study the dynamics of the entire system, as, for example, it happens or is needed in some economical studies.

3.1 The convergent structure

In a convergent model we start from an initial state *S* (the description of the formative object) and arrive at only one final state *F* (the formative target) through a series of intermediate states which refine the solution – converge to the single final state.

We represent it in this way: a pair *(S, F)* and a series of intermediate states K_1, …, K_n strongly connected. The propagation of information always stops at the successive level, in other words the model evolves step by step. Furthermore, it is always possible to start from *S* to reach *F*.

3.1.1 Example: inclined plane

The students have to acquire the Newton's second law of dynamics, manipulating the inclined plane experiment.

All the initial efforts are dedicated to individuate the law by which the acceleration is bound with the angle of the inclined plane. Once the student has acquired this notion the next step should be to understand that, considering all the forces that act on the falling body (force, mass and constraining reaction); in this case force depends on the famous equation: $F=ma$.

Let us define this experiment by defining its corresponding model. We describe its nodes (formative contents) and the connections arong levels that represent edge classes(actions).

Thus:

S (formative object) = inclined plane experiment;

F (formative target) = $(F=ma)$.

Nodes	*Edges*
$K_1 = (a=g \sin\theta)$	$(S \rightarrow K_1)$ = the system is accelerated
K_2 = direct dependence	$(K_1 \rightarrow K_2)$ = there is a parameter dependence
$K_3 = (N=mg)$	$(K_2 \rightarrow K_3)$ = the forces that act on the system are in a condition of equilibrium
K_4 = direct dependence	$(K_3 \rightarrow K_4)$ = varying θ the system looses its equilibrium
$K_5 = (Fx=mg \sin\theta), (Fy=mg \cos\theta)$	$(K_4 \rightarrow K_5)$ = the student studies the Fx and Fy components of the forces acting on the system
$F = F=ma$	$(K_5 \rightarrow F)$ = condition to extract F=ma

Obviously, during the implementation phase it is possible to expand each node at the designer's needs. This is simply the minimal required structure for this experiment.

3.2 The multi-convergent structure

Multi-convergent structure can be applied when there are different final (formative) states where the didactic system can converge to and several intermediate steps that refine the possible solutions.

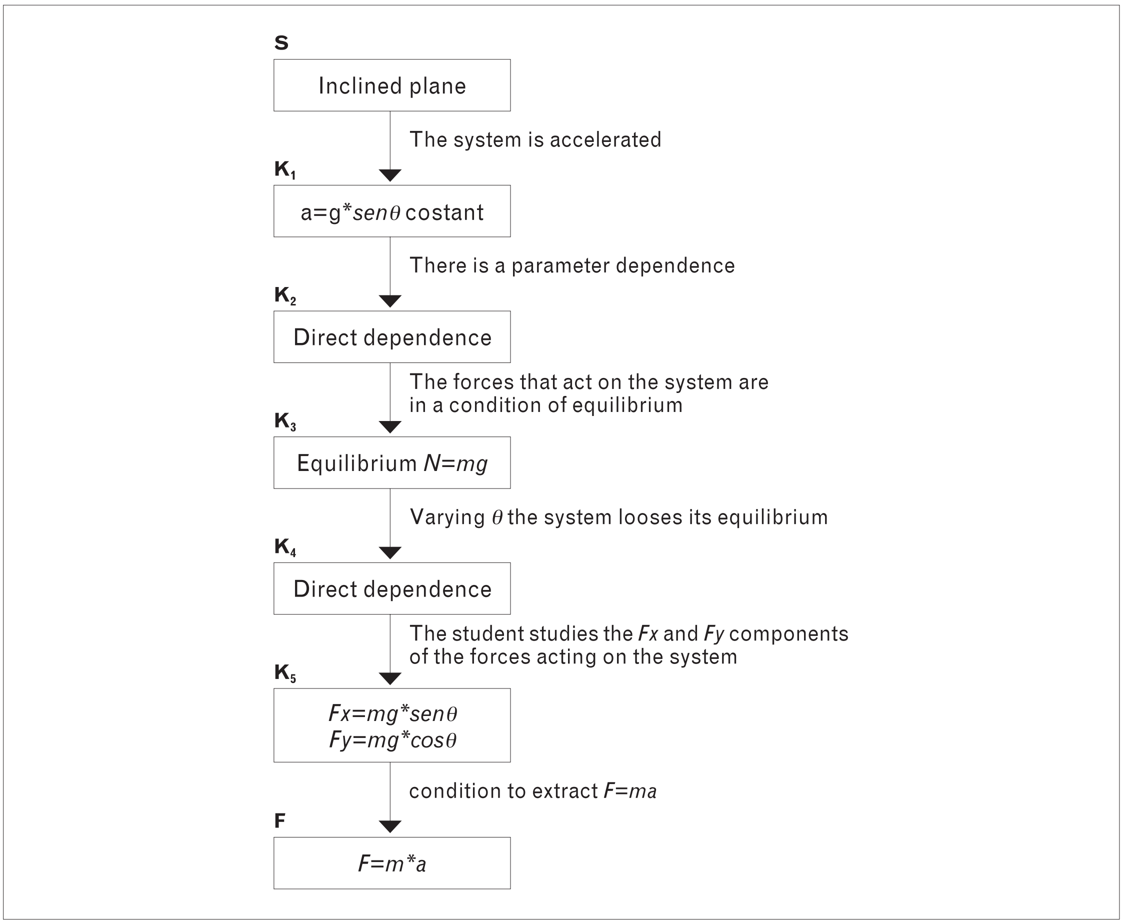

Figure 4 «Inclined plane» VSE convergent model.

Given the initial state *S*, the system arrives at $(F_1, F_2, \ldots, F_n)$ through a series of intermediate states $K_1, \ldots, K_n$. These nodes represent the constraints by which the system at the next step converges to a partial solution, until it ends at one of the possible stage $(F_1, F_2, \ldots F_n)$. We can describe this system as a pair of initial state and a set of final states $(S, (F_1, F_2, \ldots F_n))$ and a series of intermediate states $K_1, \ldots, K_n$. The propagation of information always stops at the successive node, the model evolves step by step.

3.2.1 Example: fissures in reinforced concrete beams

In this civil engineering VSE «verification of fissuring in reinforced concrete structural elements», the students have to verify when fissures in structures — of reinforced concrete — can happen.

The VSE does not provide an explanation of the law which determines fissures but it tries to show what happens if the beam is submitted to various kind of straining phenomena. In this case, there is not one final state.

Thus:
S (formative object) = a beam being under the strain of a vice;
F (formative target) = verify the dynamics of fissuring.

Nodes	*Edges*
K_1 = shape of the fissures	$(S \rightarrow K_1)$ = shape of section A
K_2 = measures of the shape	$(K_1 \rightarrow K_2)$ = measures of section A
K_3 = definition of the reinforced rod	$(K_2 \rightarrow K_3)$ = definition of the reinforced rod
K_4 = properties of the reinforced rod	$(K_3 \rightarrow K_4)$ = properties of the reinforced rod
$K_5 = (N,M)$ with N = normal strain, M = flexion momentum, f_{ctk} = concrete strength	$(K_4 \rightarrow K_5)$ = definition of the strain
F_1 , F_2 , F_3 the three possible final states (compression, fissuring, no-fissuring)	$(K_5 \rightarrow F)$ = condition to extract the three possible final states

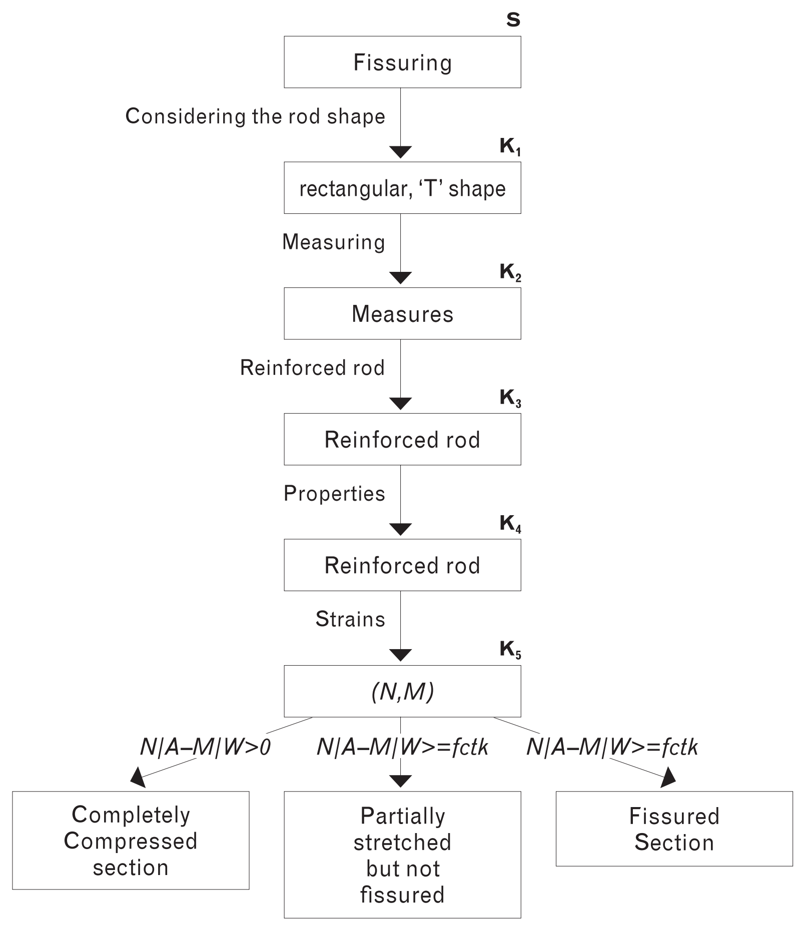

Figure 5 «Verification of fissuring in reinforced concrete structural elements» VSE multi-convergent mode.

3.3 The structure by propagation

In the model by propagation we have *n* initial states that coincide with *n* final states, the intermediate states are represented by the nodes over the time *t*. In this kind of structure there is not a final knowledge state and the formative object is detached from the formative target. This separation does not allow to represent the structure by propagation as we have already done with the other structures. Nonetheless, it is possible to build an array in which the student's interpretations are listed together with the formative object states and the time at which these interpretation are introduced. This model shows what happens when, on the one hand a determined input in a node brings about a change in the values of the other nodes following precise rules described by the edges and, on the other hand the evaluation of the student's performance (not of his/her knowledge) is needed.

The propagation of information does not stop at the next step (as it happens in the other structures) but it commits all the other steps and nodes. This structure can be seen as an array where every transformation of the system provides information and the formative object is the result value of the evolution $(x_1,\ldots,x_n)$ over the time *t*.

Table 1

TRANSFORMATIONS IN THE MODEL BY PROPAGATION

t_1	$F(x_j)$	...	$F(x_n)$	Interpretation 1
t_2	$F(x_j)$	...	$F(x_n)$	Interpretation 2
...	...	...	$F(x_n)$	...
t_m	$F(x_j)$	...	$F(x_n)$	Interpretation M

One of the most likely domains in which this model can be applied is the economical field where there is usually no single final state. In fact, in the economic systems it is often useful studying the dynamics of the entire system.

3.3.1 Example: cross-border shopping for goods

Due to the nature of the model, we formalize the «cross-border shopping for goods» VSE differently from the other two.

We can consider as input/output parameters of the simulation:

– the surfaces of the different jurisdictions;
– free circulation of goods;
– the transport cost of the purchased goods (δ);
– population uniformly distributed *(0,1);*
– the population for each country:
  • *H* in a large state;
  • *h* in a small one;

– distance from the border *s*;
– stock price *(v, V)* of the goods equal for the two countries, then the prices paid by the consumers differ just for the applied tax rate;
– a fixed tax on each retails applied on product unit;
– tax rate in the small country *(t)*;
– tax rate in the large country *(T)*.

In the simulation the agent who lives in a jurisdiction chooses whether to buy the product in his/her own country (and pay the taxes there) or cross board into the other country (and pay its taxes). The decision is taken on the basis of the following considerations:

– If V-T>v-t-∂s then the agent buys in his/her country;
– If V-T<v-t-∂s then the agent crosses the board to buy the goods.

Thus, if the small jurisdiction applies a lower rate than the bigger one, i.e. *T>t*, then all the residents *h* would buy in the small country and a fraction *(T-t)/∂s* of the large country would cross board in order to pay just the lower rate (considering the transport costs).

The chance for the consumers of choosing where to buy implies that the maximization of the internal revenue for each country depends not only on the tax rates but also on: the population number, the tax applied by the concurrent country, the transport cost and the distance of the individuals from the border.

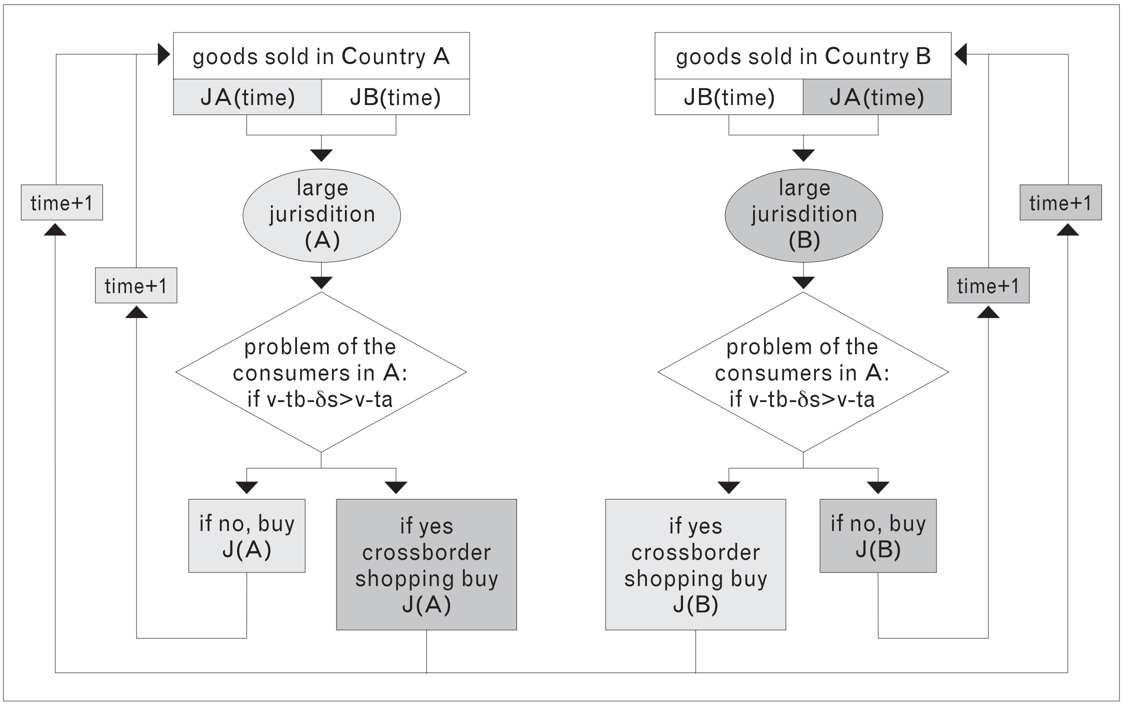

Figure 6 Dynamic of the stream of cross-border purchasing over the time.

In fig. 6, it is represented the temporal dynamic of the stream of agents' action repeated from time 1 to the moment in which the two jurisdictions will apply taxes at Nash's level.

Specifically, at time 1, the consumer who lives in *A* – following the decision rule – chooses whether to buy in *A* or *B*. The same thing happens to the consumer in *B*. At time 2, the tax base of the jurisdiction which appealed the other country consumers would be greater than the one of the jurisdiction which applied higher tax rates. The latter jurisdiction registers a loss in the tax base, since this parameter depends on *H* and *h*. The solution for the decisional problems of the individuals *H* and *h*, until the two jurisdiction do not apply rate at Nash's level, will affect the expansions and contractions of the tax bases of *A* and *B* jurisdictions.

All the nodes are mutually inter-connected. The only possible actions are to increment or decrement the values of a node following the array in tab. 2. Clearly, for each increment or decrement of a variable all the others vary, providing a new configuration the student needs to interpret.

Table 2
TRANSFORMATIONS IN THE TAX GAME VSE

t_1	$V(x_j)$	$T(x_j)$	$\partial s(x_n)$	$v(x_j)$	$F(x_j)$	Interpretation 1
t_2	$V(x_j)$	$T(x_j)$	$\partial s(x_n)$	$v(x_j)$	$F(x_j)$	Interpretation 2
...	...	...	...	...	...	...
t_m	$V(x_j)$	$T(x_j)$	$\partial s(x_n)$	$v(x_j)$	$F(x_j)$	Interpretation M

4. Conclusion

We provided a modelling analysis based on the relation between the knowledge domain (formative object) and the formative target of VSEs. The distinction and characterisation of each model depends on the set of properties which its dynamic fulfils at a specific level of abstraction. We indicated why and how these systems can be considered models.

Three philosophical approaches correspond to the models. They define the knowledge the student builds up when using the VSEs. The convergent model refers to nomological-deductive explanations; the multi-convergent model to cybernetic explanation; the model by propagation to structural explanation.

In the nomological-deductive explanation, as long as a particular event («this metal bar is expanding») is under a covering-law, it can be intended as the final step of a deduction («all metals expand when they are heated, this bar is a metal bar and it is heated. This bar expands»). When VSE is represented by a convergent model, the student should build up the knowledge of a physical law by manipulating the experimental parameters composing the law equation. The knowledge he/she obtains is rigid, each intermediate step must be determined and the outcomes must match the formative target. Then, the student recreates the same structure of nomological-deductive explanation we have considered: he/she univocally determines what physical law can explain a specific fact or event. In other words, the student is invited to learn a law and to use it in a specific explicit scheme.

Given a system, the cybernetic explanation considers the alternative states which could have been reached by it and then asks why it did not happen. Bateson's words:

> «Causal explanation is usually positive. We say that billiard ball B moved in such and such a direction because billiard ball A hit it at such and such an angle. In contrast to this, cybernetic explanation is always negative. We consider what alternate possibilities could conceivably have occurred and then ask why many of the alternatives were not followed, so that the particular event was one of the few which could, in fact occur [...].»

In the VSE multi-convergent model, the student manipulates a system in order to observe how it ends at diverse solution spaces. The possible final states are represented by multiple solutions where the initial state and the intermediate steps converge to. Then, the explanation is about (a) the different possibilities that determine the dynamics of the system, (b) why the system causally ends at that very solution, and (c) why not the alternatives. The student learns the possible structure of the model by studying the states of the system, even if the considered case shows only one state.

In the structural explanation the behaviour of a system is characterized by the set of relations connecting its elements. In logical terms, a relation between a set *A* and *B* is considered as an other set *R* containing a specific subset of the ordered pairs of *A* and *B*. A structure is another set *S* with a series of *R*s as elements. Specification of *S* represents a structural explanation. In the model by propagation, the student learns that an intervention on a network node effects the behaviour of the entire system. The VSE invites the student to interpret the transformations of the systems and its causal structure: the knowledge is based not on a specification of the solutions (more or less convergent), but on understanding which strategies of parameter modifications can produce the desired transformation.

This proposal needs to be further elaborated; it could be worthwhile to discuss how the three models can improve the VSEs design and implementation.

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