# What is learned in system dynamics education: a competency-based representation based upon Bloom's taxonomy

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*Abstract*
System dynamics is progressively taught in different levels of education systems, and there are challenges as for integrating it into the curricula of different professions and at the same time striving to grow it into a profession on its own. This paper starts recognizing that no representation of what is learned in system dynamics has been published in a way compatible with mainstream curricular tools. Specifically the need to integrate system dynamics into a competency-based curriculum has lead to a search in the field. We have opted for "Bloom's taxonomy" as a widely shared reference frame and thus have expressed cognitive resources and development indicators in Bloom's terms. The result is now a valuable resource for incorporating elements of system dynamics across different courses of undergraduate programmes in our university. Even so, the result has to be critically revised, for there are several open questions concerning the development stages of the learning process and the best form of representing them in order to facilitate the design and development of learning and assessment activities.

*Keywords*: SD education, competencies, Bloom's taxonomy

## Introduction

Several years ago, the "Universidad de Talca" in central Chile embarked on the road towards competency-based higher education. At the same time, system dynamics started to be taught as an elective for students of business administration. As can be expected, there was a need to explain what you learn when you learn system dynamics, if possible in disciplinary terms colleagues and authorities are familiar with, in a way that is compatible with competency-based education. On top of this, it should allow a course to be evaluated: since the competence-based curriculum is new for us, courses must be assessed and improved from term to term [3]. Over the past five years, system dynamics has grown – slowly – and is now being used in courses on "knowledge construction", supply chain and macroeconomics. This expansion has made it even more important to have a representation of what is learned in system dynamics that satisfies the criteria mentioned above.

The search for a convenient way of articulation started with the examination of what already existed. System dynamics is currently taught in rather diverse settings and levels of the education system. One can enrol in one of the few doctoral programmes or go through one of the master programmes (see Doyle et al., 2009 for a clear example). In these cases, substantial time will be spent studying the abstract concepts and methods of the discipline. One can also encounter system dynamics in undergraduate programmes at a growing range of universities; in these cases, it is usually inserted into the concrete context of a profession or scientific discipline

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[3] Also keep in mind that a large share of students are at odds with the English language, so that existing materials can hardly be used.

like management or engineering, for instance. In several countries, system dynamics is also making its way into the school system, where it may be part of subject matters like mathematics or sciences.

For studying system dynamics at the university level, there is a standard set of classic texts (Morecroft, 2007; Sterman, 2000; Forrester, 1961, ordered from the present to the past) and study materials (Roadmaps). For schools, the materials from the Creative Learning Exchange and the books by Diane Fischer (2001; 2004) play the same role.

There seems to be a shared tacit understanding of what it is one has to learn in order to become a dynamicist: one should know what makes up a stock-and-flow diagram, a causal loop diagram, understand the principles of systems, know the basic structures of feedback systems, know and be able to perform the phases of the modelling process … most dynamicists know how hard it is to express what system dynamic is.

However, since usually system dynamics will be part of educational programmes in established fields like engineering or business administration, place has to be made in existing programmes, and questions like "what is system dynamics" will be asked by people who do belong to other communities. Under these circumstances, having an answer to this first question - a generally understandable articulation of what system dynamics is - would be of advantage.

Then comes the question of how it can be learned in a convenient manner. When reflecting upon the process of learning system dynamics, there will always emerge an image of a progressive process:

1. Use classic and/or standard models before starting to build your own models;
2. Use simple tools (CLDs) before using more complex ones (stock-and-flow modelling);
3. Model simple situations before modelling more complex ones.

However, each of these statements can be called into question. Using objects before trying to build them on one's own may seem straightforward, but for those underwriting a constructivist (Piaget, 1955) or constructionist (Papert, 1993) standpoint, where knowledge is constructed while constructing the object, it is questionable to believe that mere use will lead to significant learning effects (and this is a stance that the dynamicist discipline defends). The use of simple tools is overshadowed by their serious limitations (Lane, 2008; Schaffernicht, 2010). Modelling simple situations before modelling more complex ones is certainly a sensate recommendation; however, it is not very informative about how to learn to model, since "modelling" is used in a recursive manner.

Inspection of the tactics inherent in major learning objects leads to some interesting discoveries. Sterman's "Busyness Dynamics" (Sterman, 2000) is a very complete work, which seems to somehow follow all three ideas mentioned above: it mainly deals with standard models that are presented at once (rather than "modelled" step by step); CLDs are used to discuss each basic structure before advancing to stock-and-flow models, and the basic structures go from simple feedback loops towards ever more complex combinations. Morecroft's "Strategic dynamics" (Morecroft, 2007) takes a different route, putting more emphasis on the process of modelling (rather than "using" each model). It privileges stock-and-flow models over CLDs. However, the progression from simple feedback structures to more complex structures is maintained. We clearly see a different set of choices. Still another configuration is chosen by Diane Fischer in her exercise books (2000; 2004). There, resolving problems by constructing a model is the main theme; no CLDs are used, but the exercises move from simpler structures to more complex ones.

We can draw some inferences from these three examples: first, it is clear that the examples should go from simple to complex. Second, most readers who were not experts before reading these texts will have found Morecroft's or Fisher's work easier to go through than Sterman's, while the latter will be the preferred book for experienced dynamicists. This means that the intuition behind "use before create" is not confirmed.

Nevertheless, those who wish to help students learn system dynamics cannot know how to organize their activities and materials from inspecting these books: they do not make explicit what their respective authors assume to be the progression of learning. Even though some insight is offered by some designers of programmes (Doyle et al., 2009), this tends to be an exception.

Such an underlying structure should be searched for in the realm of education. And indeed, a construct called "Bloom's taxonomy" has been developed for over 50 years now. However, it is only seldom referred to in system dynamics. Stave and Hopper (2007) and Hopper and Stave (2009) use this taxonomy, but they elaborate a systems *thinking* taxonomy. A search on Google's "scholar" database yields 2 hits: in 1978, Roberts explored the use of systems *thinking* in education and used this taxonomy for her assessment. In 1989, Klein mentioned it in the context of using bicycles to teach system *dynamics*.

Systems *thinking* is closely related to system *dynamics*, and it certainly shares the same worldview and some cognitive skills and conceptual knowledge. Even so, system *dynamics* comprises skills and concepts that go beyond systems *thinking*. Therefore, these previous contributions will not be able to respond our first question.

There are two open questions:

1. What components make up system dynamics?
2. In which sequences can they be learned (and should they be taught)?

These are relevant questions in order to achieve insertion of system dynamics training in educational programmes and also to allow the development and sharing of educational designs and objects.

This need to articulate "that which is learned" in a system dynamics course in the context of a competency-based curriculum, has conducted the authors to use Bloom's taxonomy as the "language". Accordingly, all the learned entities have been labelled with verbs taken from this taxonomy, and grouped into clusters following Bloom's 6 progressive levels and then connected into a sequence. The result is twofold: first, we propose an explicit image of what system dynamics is in terms of conceptual knowledge and cognitive skills. Second, we also offer one way to chain these components together into a learning itinerary.

In our university, the first aspect is used to relate this course to others. However, it is also an adequate object in order to discuss what is learned when someone studies system dynamics. The second aspect is used to design learning activities that can be monitored and continuously improved, as will be shown below. It must be said that more than one itinerary can be devised and only in-field experimentation and comparison can shed light on which ones work better.

By submitting our design to the community, we hope to trigger a critical dialog on both aspects, which will help advancing our knowledge on "learning system dynamics" and help the field to develop a shared language on this subject.

The paper is structured in the following way. The second section introduces into the main topics of competency-based education and Bloom's taxonomy. Then the third section discusses the conceptual network which describes "learning system dynamics". The fourth section explains how it is being used and what is planned for this year, as well as opening some topics of future development. The conclusions are preliminary, as this is a topic "in progress".

## Fundaments

### *Competencies*

Competency-based education has been in the literature since more than 30 years (Burns, 1973), and in its simplest definition it is synonymous to "ability". However, more specific definitions have been developed, providing more details that help to organize a curriculum. On its way towards competency-based education, our university decided to follow the experience and the conceptualization of the Sherbrooke university (Tardif, 2006), where it has been successfully developed and used. Here we will limit ourselves to the essential concepts and definitions.

In this case, *competency* is defined as a "knowing-to-act by successfully combining internal and external resources in a family of situations". Going beyond "knowing how to do" something, "knowing to act" includes successfully diagnosing the situation and deciding what to do. Internal *resources* are the different kinds of knowledge (see below, in the section on Bloom's taxonomy). A *family of situations* is a set of situations that have shared characteristics, usually belonging to a professional field or a specific part of it. Any competency is a domain of lifelong learning, and it develops in *stages*. Learners develop from stage to stage by events of conceptual change, which makes these irreversible. Each stage is described by a specific set of *indicators* concerning the actions, the resources and the learner's degree of autonomy. Performance standards are expressed according to these indicators, which are developed as rubrics in order to monitor de learning process.

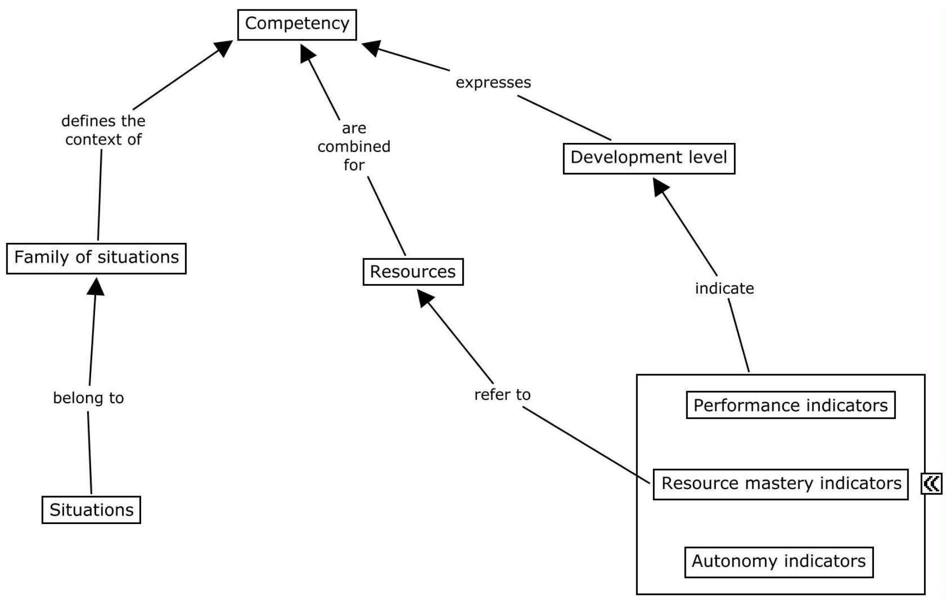


*Figure 1: the conceptual architecture of "competency"*

According to the previously mentioned concepts, a first question must be if "system dynamics" is a *competency* or a *resource*. In our case, there is no simple answer: for our business students, it is a *resource* and used to resolve supply chain situations and macro-economical problems. At the same time, the "knowledge construction" course considers it as a *competency*. Therefore, the formulation to be found in this paper attempts to be useful in both situations.

In order to approach the competency, we start out referring to one pregnant expression of what the system dynamicist produces came from Forrester (2007: 363):

"Through an appropriate simulation model, one should *know the structure causing the problem*, should *know how the problem is created*, should have *discovered a high-leverage policy that will alter behavior*, should *understand the reasons why the low-leverage policies will fail*, should *be able to explain how strongly defended policies within the system are actually the cause of troubles*, and should *be able to argue for better alternative policies*."

So if system dynamics is the development of such an appropriate simulation model, and through it the mentioned knowledge (or mental model, see Schaffernicht, 2010), how shall the *competency* be called, what are the *stages* learners go through, what are their respective *indicators*, what are the *resources*, and eventually: what are the *situations* and their *family*?

Developing answers to these questions is a process that goes through stages itself, and the current version has to be critically assessed. Still, what is described in this paper respects these concept definitions and the data structure they imply.

*Bloom’s taxonomy*

Each community of practice develops certain ideas and its own language. Many educators – and this paper is written from the educator’s perspective – use “Bloom’s taxonomy” (Bloom, 1956). Benjamin Bloom was interested in the mental processes of learning; in this context, he developed a taxonomy of learning goals in terms of mental processes. Its underlying idea is that higher level capabilities (or learning goals) require preceding lower capabilities to be accomplished beforehand. This was thought to be true in three domains: affective, psychomotor and cognitive. Accordingly, the taxonomy organizes the universe of capabilities in each domain (expressed as verbs) in different levels.

In the affective domain, there are five progressive levels:

- receiving (without which nothing else can be done);
- responding (to stimuli);
- valuing (showing a personal perspective);
- organizing (establishing relations between issues);
- characterizing (values and beliefs that influence behaviour).

The psychomotor domain deals with being able to perform the movements necessary to manipulate the external world. Since they are not relevant for system dynamics in this case, we only mention this domain without entering into details.

The cognitive domain was the first to be specifically developed and has undergone several revisions and reformulations (Andersen et al., 2001). Its levels are displayed in the following figure:

| ***Knowing*** | ***Understanding*** | ***Applying*** | ***Analyzing*** | ***Creating*** | ***Evaluating*** |
|---|---|---|---|---|---|
| *- define* | *- predict* | *- apply* | *- separate* | *-decide* | *- combine* |
| *- list* | *- associate* | *- complete* | *- order* | *- grade* | *- integrate* |
| *- label* | *- estimate* | *- illustrate* | *- explain* | *- test* | *- reorder* |
| *- name* | *- distinguish* | *- show* | *- connect* | *- measure* | *- plan* |
| *- identify* | *- recapitulate* | *- examine* | *- divide* | *- judge* | *- invent* |
| *- repeat* | *- describe* | *- modify* | *- compare* | *- explain* | *- What if?* |
| *- who?* | *- interpret* | *- relate* | *- select* | *- Value* | *- prepare* |
| *- what?* | *- discuss* | *- classify* | *- explain* | *- criticize* | *- generalize* |
| *- wneh?* | *- contrast* | *- experiment* | *- infer* | *- justify* | *- compose* |
| *- where?* | *- explain* | *- descover* | *- lay out* | *- support* | *- modifiy* |
| *- count* | *- paraphrase* | *- use* | *- classify* | *- convince* | *- design* |
| *- describe* | *- illustrate* | *- compute* | *- analyze* | *- conclude* | *- hipothesize* |
| *- examine* | *- compare* | *- resolve* | *- categorize* | *- select* | *- invent* |
| *- cite* | | *- construct* | *- contrast* | *- predict* | *- develop* |
| | | *- calculate* | | *- argument* | *- re-write* |

**M a t u r a t i o n**

*Figure 2: Bloom's taxonomy. Complexity (maturation) augments from left to right (Own elaboration based upon Andersen and Krathwol, 2001.).*

In this figure, the different levels are color-coded: knowing is blue, understanding green, applying yellow, analyzing orange, creating maroon and evaluating pink. This is important for examining the concept map discussed below, where these colours are used to distinguish the Bloom levels. The revision has produced some modifications: the word forms were changed to verbs (substituting “evaluating” for “evaluation”), and the two highest levels – synthesising and evaluating – were interchanged; some also changed “synthesising” into “creating”. According to Huitt (2009), there is an ongoing debate about the relation between these two levels, and some scholars propose to consider both as belonging to the same level.

Also, several types of knowledge have been distinguished:

- Factual;
- Conceptual;
- Procedural;
- Meta-cognitive.

It can be argued that in cases like learning system dynamics, attention will center on conceptual and procedural knowledge, since they lend themselves for connecting with the competency-based educational world and its notion of internal resources.

Originally proposed half a century ago, it has helped educators talk and think about their goals in a shared language. There are several features that make this taxonomy attractive for teaching system dynamics:

- it offers a set of verbs that can be used to describe any human activity;
- a large share of scholars and practitioners are familiar with it and we can draw on their resources;
- it recognizes a progressive development of capabilities in a way that is compatible with what be know about learning system dynamics.

Therefore, Bloom's taxonomy has been chosen as the language to express the progressive learning of system dynamics.

## Learning system dynamics competencies

*Overview*

System dynamics as a competency first needs a general definition. A look at some sources intended to give newcomers a first information will contemplate the society's website [4], where a short description has been offered (I believe by David Lane). Additionally, the system dynamics wiki resumes various responses to Fabian Szulansky's challenge of defining system dynamics during a 30 seconds elevator ride [5]. All these statements mention essential elements, but they are not expressed as competency.

In our courses, we currently state it the following way: "*develop* a conceptually and behaviourally **validated simulation model** of a <u>dynamic situation</u> that enables to *understand* the **causal structure** and how it generates the <u>situation</u>, to *explain* high leverage **policies** and their advantages over alternative **decision policies** and to *explain* and *argument* for the conditions for successful implementation". Of cause, this definition draws heavily on Forrester's statement (above). The verbs in italics point to elements in Bloom's taxonomy; boldface words are the objects that successful action will produce; the underlined parts represent the family of situations (in a very abstract way, allowing to insert system dynamics into any professional field where decision policies for dynamic situations are relevant; since these situations have to be defined for each respective course, they are not treated here). All other elements are relegated to the part where the internal resources and the indicators are stated and combined.

At the current moment, there is no systematic account of the stages a learner goes through during his transformation into a system dynamicist. As mentioned in the introduction, one could intuitively argue that before becoming a good developer of new models, one should have understood the relevant established models in the domain one acts in. This is reminiscent of Forrester's vision of the next 50 years of the field (2007). However, the same author always has argued that a profound understanding will come from going through the process of modelling,

[4] http://www.systemdynamics.org/what_is_system_dynamics.html

[5] http://www.systemdynamics.org/wiki/index.php/System_Dynamics_Elevator_Pitch

rather than the interaction with readymade models (1985); as discussed by Schaffernicht (2010), arguably students will have to rediscover such models (by guided re-construction). The brief inspection of currently used learning materials (above, in the introduction) has already suggested that the activity *to develop models* will be central to learning system dynamics from the start: it is unlikely that a stage *to exploit models* will precede this.

In the face of no existing cognitive theory of how system dynamics is learned and the need to keep teaching it every semester, the current formulation of the competency assumes that all resources and indicators can be laid out in one single development level and will not be separated by jumps of conceptual change. Nevertheless, there probably are such moments of conceptual change. Anecdotic evidence suggests that some deep moments of "aha!" occur when a person recognizes the ubiquity of "feedback loops" and similar experiences take place when someone recognizes the principle of correct stock-and-flow thinking. However, we do not know how these moments and their effects relate to the ability to develop system dynamics models. Therefore, there is a need to study this domain, and hopefully the current formulation will serve as a first step which can be criticized and improved upon.

We will now proceed in two steps: first, the resources and their indicators will be introduced, and then they will be combined in a way that is coherent for system dynamics's work process. The resources and indicators are represented as brief phrases consisting of an activity (a verb taken from the taxonomy) and an object. The objects are:

- Concepts
  - Structure
    - Variables (accumulation, flow, auxiliary)
    - Links, Delays, Polarity
    - Loops, Polarity
    - Models (CLD, S&F)
    - Generic structures (R+, R-, R+-,R+--,delay types, chains, co-flows)
  - Behavior (exponential, logarithmic, "S", oscillation, overshoot and collapse)
  - Decision policies
- Methods
  - Model (Define problem, Conceptualize, Quantify, Validate, Exploit),
  - Loop detection
  - Loop polarity detection

Consider next the resources and their indicators, organized by levels of Bloom's taxonomy. Since for each cognitive resource, there are one or several indicators, such a description has at least two levels of hierarchy. By consequence, there are two ways to construct such a hierarchy: stating the resources and then decomposing them into indicators or stating the indicators and then compose the resources. In the authors' opinion, it is safer to choose the second alternative: the elementary aspects of doing system dynamics appear to be clear to all the members of the community, while there may be disagreements when it comes to grouping them together into higher order units. Therefore, we now present the list of indicators, grouped only by their membership in the respective levels of Bloom's taxonomy.

**Level 1: *KNOWS* system dynamics modeling**

- *Defines* the objectives of SD
- *Lists* the phases of modeling
- *Defines* the function of each step in the modeling process
- *Defines* the activities of each phase of the modeling process
- *Defines* the methods applied in each phase of the modeling process
- *Defines* dynamic complexity
- *Defines* the conditions for applying SD

**Level 1: *KNOWS* the concepts of SD**

- *Identifies* the types of variables
- *Defines* polarity
- *Defines* accumulation
- *Defines* flow
- *Describes* the difference between accumulation and flow
- *Defines* the rules of graphic integration
- *Defines* the rules of graphic derivation
- *Defines* the method of loop detection
- *Defines* the method for detecting loop polarity
- *Identifies* generic behavior modes
- *Describes* generic behavior modes
- *Identifies* generic structures
- *Describes* generic structures

**Level 2: *UNDERSTANDS* the concepts of SD**

- *Explains* the types of variables
- *Associates* generic behavior modes to generic structures
- *Associates* generic structures to generic behavior modes
- *Interprets* BOT graphs
- *Describes* a stock's behavior given the flows
- *Describes* a flow's behavior given the stock's values
- *Predicts* a stock's behavior given the flows
- *Predicts* a flow's behavior given the stock's values

**Level 3: *APPLIES* the steps of the modeling process**

- *Discovers* the variables implied by a discourse
- *Classifies* the variables by type
- *Classifies* the variables' units of measure
- *Discovers* causal links implied by a discourse
- *Classifies the* links' polarities
- *Discovers* delays
- *Computes* flows from data about successive stock values
- *Discovers* the shape of the causal relation between two variables.
- *Constructs* a CLD based upon a S+F diagram
- *Constructs* a S+F diagram based upon a CLD
- *Experiments* with simulation models to assess proposed hypotheses.
- *Resolves* problems using simulation models.

**Level 4: *ANALYZES* models**

- *Infers* feedback loops
- *Classifies* the loops' polarities
- *Analyzes* and *explains* CLDs (structure and behavior)
- *Analyzes* and *explains* S+F models (structure and behavior)
- *Compares* a model with similar models.

**Level 5: *EVALUATES* situations in modeling terms**

- *Prepares* a modeling project
- *Establishes* a problem (with logical and temporal scope)
- *Establishes* the purpose of the modeling work

**Level 5: *JUDGES* the validity of a simulation model**

- *Tests* model's structural validity
  - *Tests* dimensional consistency
  - *Tests* each variable's correspondence to a real entity
  - *Judges* a model's membership of a model family
- *Tests* models' behavioral validity

*Measures* the historic fit
*Tests* extreme condition behavior
*Tests* the sensitivity

**Level 5: *EVALUATES policies and problems***

*Explains* the causal structure of a problem or situation
*Explains* how the problem is created by this structure
*Explains* why one policy has high impact while others fail to do so.
*Explains* how established and defended policies are the underlying cause of the problematic behavior.
*Argues* in favor of better policies.

**Level 6: *SYNTHESIZES (CREATES) models***

*Proposes* hypotheses in the context of a problem (based upon a S+F model)
*Proposes* hypotheses concerning the behavior of variables in generic structures
*Designs* a qualitative (conceptual) model (CLD or S+F)
*Designs* a quantitative S+F model (Quantifies the variables)
*Modifies* the S+F model to achieve validity (Validates the S+F model)
*Modifies* the model to test scenarios or candidate policies (Exploits the S+F model)

Each of the indicators describes some kind of knowledge or skill applied to an object belonging to system dynamics. Additionally, it has been assigned to one level of Bloom's taxonomy, implying that some aspects are simpler and others more complex. This is the first part of the construct we propose, and for each of these elements, the reader can agree that it is part of system dynamics or he can disagree, without compromising the next step.

This being said, by cutting system dynamics in so many little pieces –so to say- the wholeness is analytically destroyed and a need to establish relationships emerges, such as to reunite what has been separated. The nature of system dynamics is such that it does not exactly coincide with the delimitations between the levels of Bloom's taxonomy. Therefore, it becomes necessary to establish relationships between the elements and thus assemble larger chunks of indicators.

We will use several types of relationships between indicators:

| Relationship type | Example |
|---|---|
| is-part-of | "Designs a qualitative (conceptual) model (CLD or S+F)"<br>is-part-of<br>"Develops modeling projects" |
| | "Applies modeling phases Constructs qualitative models (conceptual)"<br>is-part-of<br>"Designs a qualitative (conceptual) model (CLD or S+F)" |
| precedes | "Defines the rules of graphic integration"<br>precedes<br>"Describes a stock's behaviour given the flows" |
| sequence | "Designs a qualitative (conceptual) model (CLD or S+F)"<br>sequence<br>"Designs a quantitative S+F model<br>(Quantifies the variables)" |
| is-done-before | "Develops modeling projects"<br>is-done-before<br>"Evaluates policies and problems" |

Text is not a good representation format to adequately capture the way these relationships connect different elements, forming groups and/or clusters. Concept maps are able to represent such relationships in a readable manner; in that format, the indicators appear as nodes and most of the relationships as lines. Each of the examples in the table above is taken from one of the concept maps that will be presented below. In the first case, the first node is collapsed into the second (which is able to group several such nodes together). In all the other cases, a line with a corresponding label links the nodes together.

The following figure shows concept map in which the nodes have different colors (blue means knowing, green understanding, yellow applying, orange analyzing, maroon creating and pink evaluating) [6].

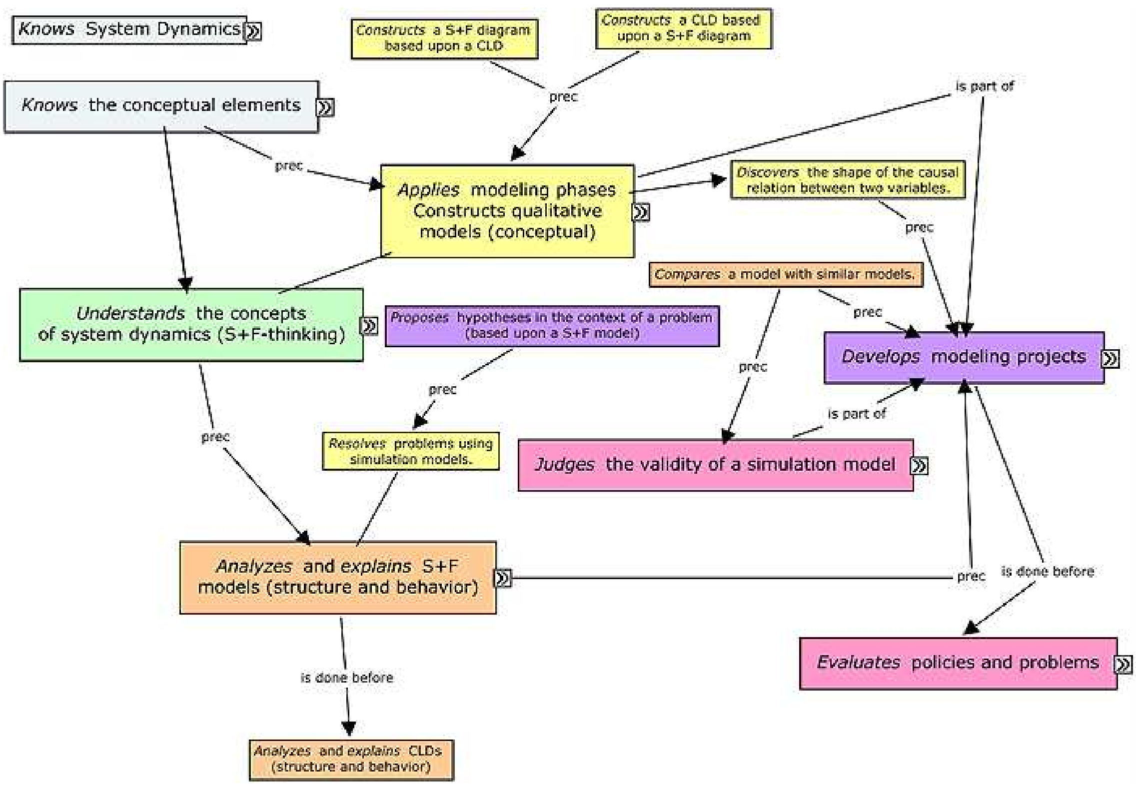


*Figure 3: collapsed concept map*

In this map, some nodes are printed in larger letters; these are chunks of indicators that have been grouped together to form a "resource" of system dynamics. These resources mostly are related to a specific level of Bloom's taxonomy, like in the cases of "knows system dynamics", "knows the conceptual elements" and "understands the concepts of system dynamics". In these cases, the set of sub-nodes is the set of indicators that appeared in the above list. However, this is not always the case, as will be shown below. This is due to the fact that some resources or major SD activities comprehend activities that belong to different levels of the taxonomy.

The indicators and resources are mainly organized by "precedes" relationships according to their respective levels in the taxonomy: knowing -> understanding -> applying. Interestingly, applying and validation appear as being "part of" developing modelling projects. This articulates a theory of learning, according to which lower level skills are learned before higher level skills, because they logically precede them: first the learner shall "know" (recognize) the conceptual elements, second he shall "understand" them. Both are previous conditions for

[6] An image of the complete map is available as supllementary material. The original map requires installing "CMapTools" (freely available at www.ihmc.us) and can be obtained from the corresponding autor.

applying them in model construction and model analysis. Model construction is one part of the process of model development, another one is validation. And the finality is to evaluate policies and problems.

A second aspect is that this is not a clear-cut conceptual model (since there are nodes that are hard to group and some things have been analyzed apart but belong closer together (connected by the “is part of” links).

Due to the extension of the whole map, it is not possible to view it on one page without printing the words in reduced font sizes (following page). We will therefore break up the map by levels of Bloom’s taxonomy and discuss them separately (accepting that inter-level links will be cut).

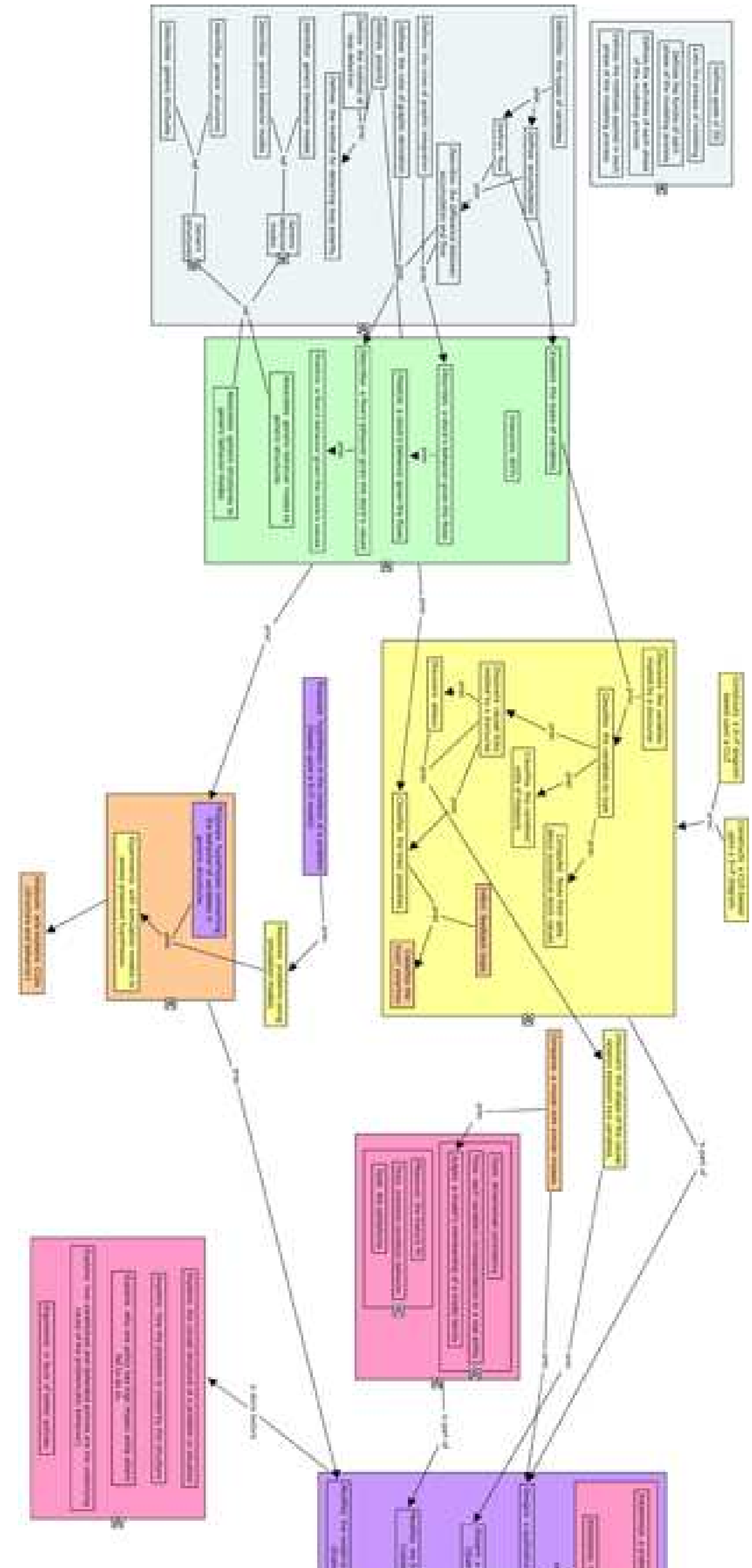

*Figure 4: the concept map with all nodes*

*The different levels of Bloom's taxonomy*

A closer look at the cluster nodes will allow to discuss both aspects in a more detailed manner.

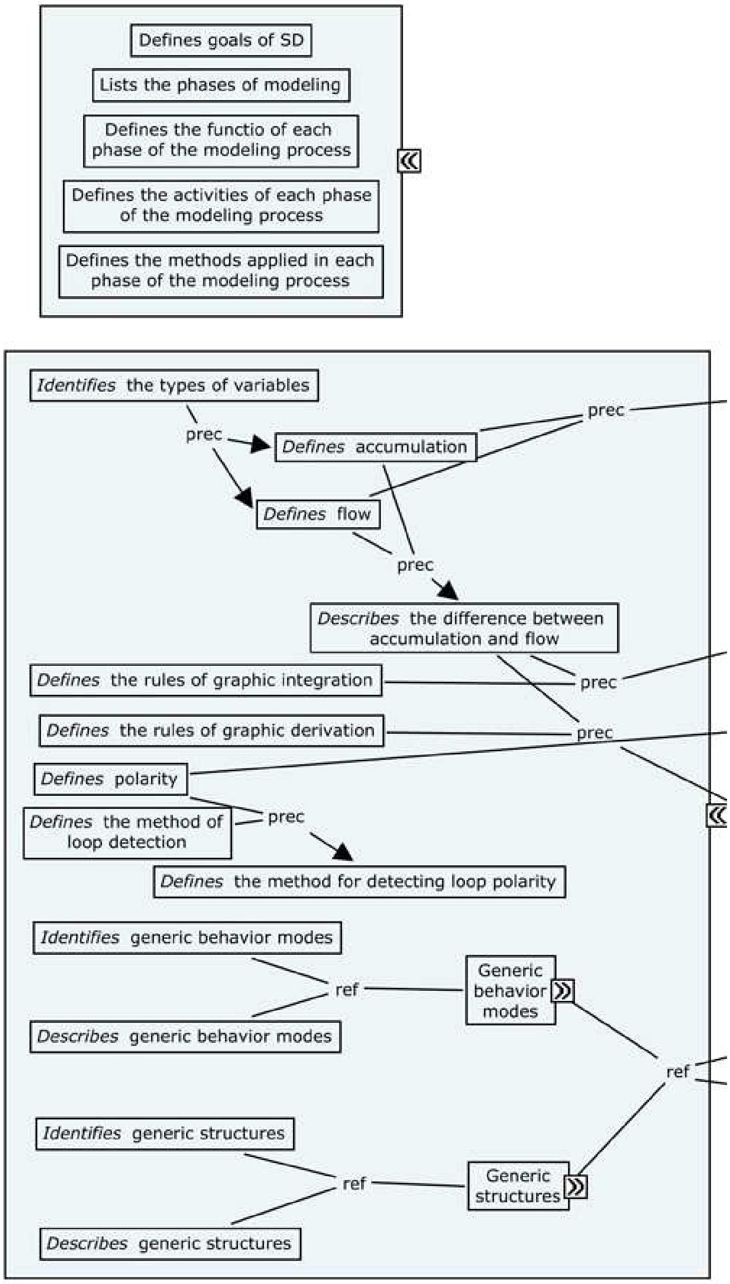


*Figure 5: Knowing (remebering): "knows system dynamics" and "knows the conceptual elements"*

The figure displays "knows system dynamics" and "knows the conceptual elements", two groups of indicators. Since the former refers to the modeling process and the latter to conceptual elements, they appear not to be connected by any of the defined relationships. In the first group, students are described as being able to *list* (the names) and define (recall the definition) of system dynamics as a whole, the phases of the modeling process, their goals and components. In the second group, the student's abilities are expressed by *identifies* (gives the name), *defines* and *describes*. The objects of these activities are the fundamental types of variables, their relationship, the polarity and the loop concepts and the generic behavior modes and causal structures, as well as the relationship between them.

Many times, *identifying* precedes *defining*, which in turn precedes *describing* – this is a deliberate ordering, and it is a choice which could have been different. However, in our design this is a logical precedence rather than a temporal one: you can expose students to descriptions without having defined the terms; however, in order for a description to be meaningful, its terms have to be defined, and this requires previously giving them names (identitifiers). The concept map also contains two cluster nodes that only contain objects (the generic behaviors and the generic causal structures); we chose this way to present the case in order to avoid having to repeat the abilities that have to do with generic entities (or not making explicit which generic structures and behaviors we are talking about).

Taken together, this anchors a basic vocabulary and a conceptual seed which prepares the stage for the next level.

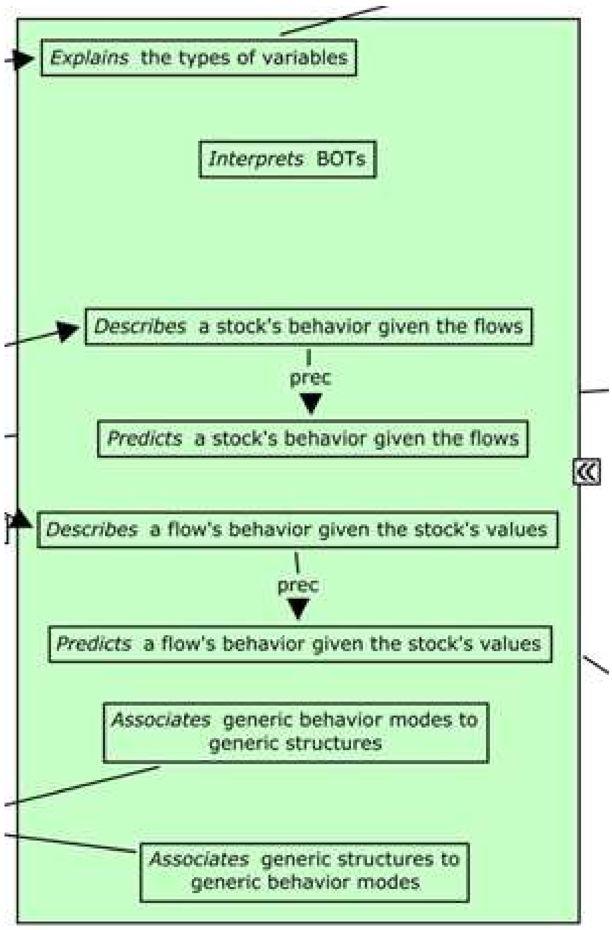


*Figure 6: Understanding the concepts of system dynamics*

Figure 6 represents the stage "understands the concepts of system dynamics (stock-and-flow thinking)". Now the dominant abilities are *explaining*, *interpreting*, *predicting*, *associating* and (again) *describing*. The objects are stocks, flows, the rules connecting them and the behavioral implications that are many times called "stock-and-flow thinking". Predicting is preceded by describing, because the ability to predict, that is to say: describe a future behavior, certainly is the fruit of having described past behaviors.

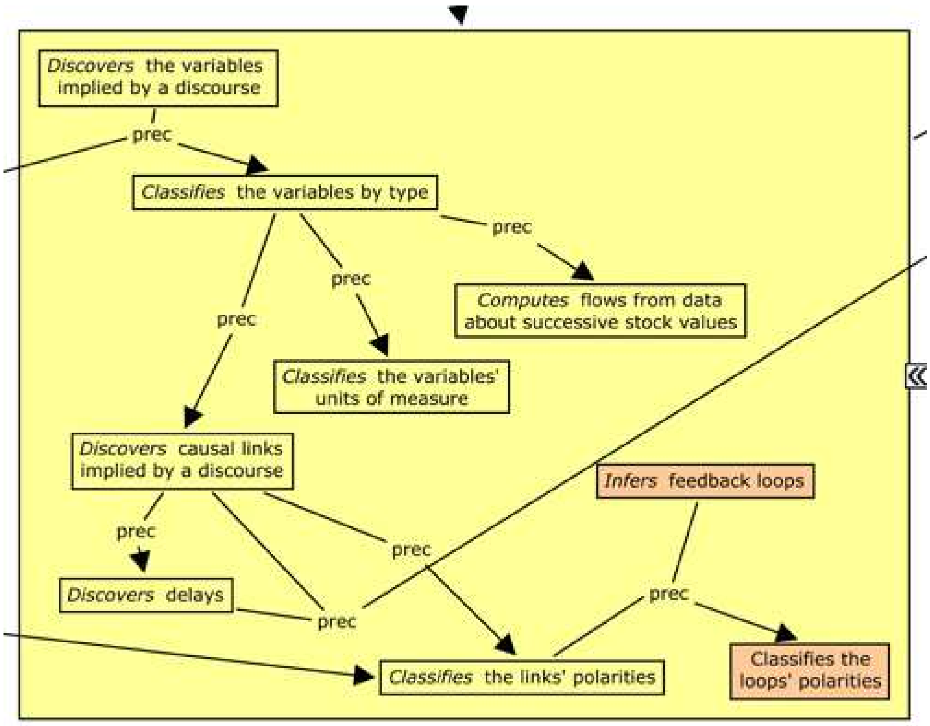


*Figure 7: Applying*

Figure 7 shows the level "applying the modeling phases (constructing qualitative models)". The abilities are described as *discovering*, *classifying* and *computing*. Now the activities are more complex than recalling or expressing understanding, since the learner has to apply these known and understood entities to situation (discourses) he is confronted with. Even if this is not full scale simulation modeling, it is already an application of system dynamics.

Two nodes have been borrowed from the next level, since they imply analyzing the model structure and inferring feedback loops and their polarity). This documents our impression that Bloom's taxonomy is not applicable to the case of system dynamics without difficulties. Still, since it is not our aim to prove that the levels of the taxonomy are always sequential and its member activities (verbs) are never executed together, we do not consider this as a problem.

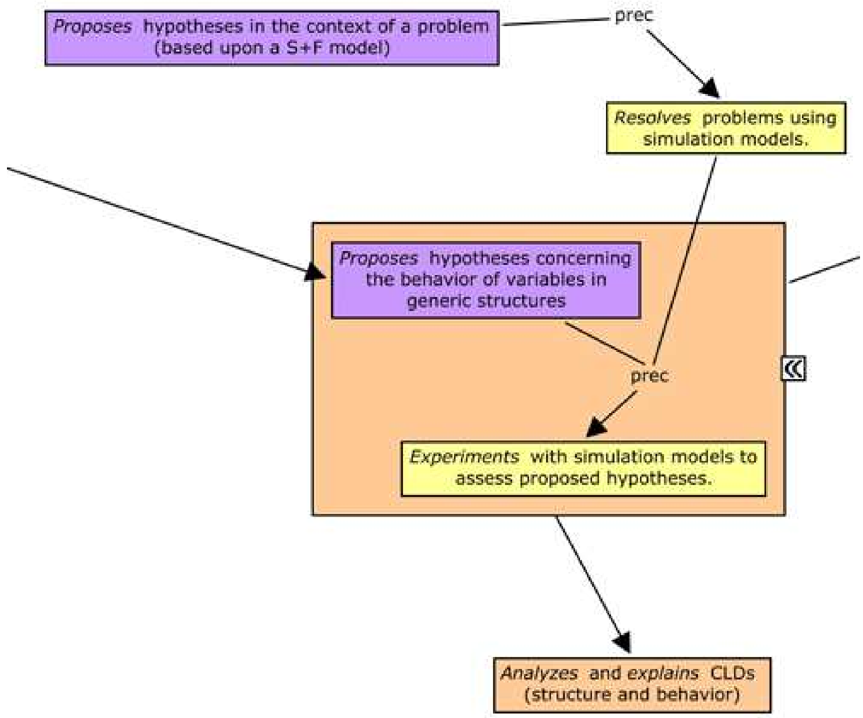


*Figure 8: Analyzing*

"Analyzing and explaining stock-and-flow models" is represented in Figure 8, with activities of a higher order: *resolving* problems, *proposing* hypothesis, *experimenting* with the simulation model and using this knowledge to analyze and *explain* qualitatively the causal structure of a problem. These activities draw upon the accumulated knowledge and capability from previous stages, and they will also continue developing the learner's abilities in the lower levels of the taxonomy.

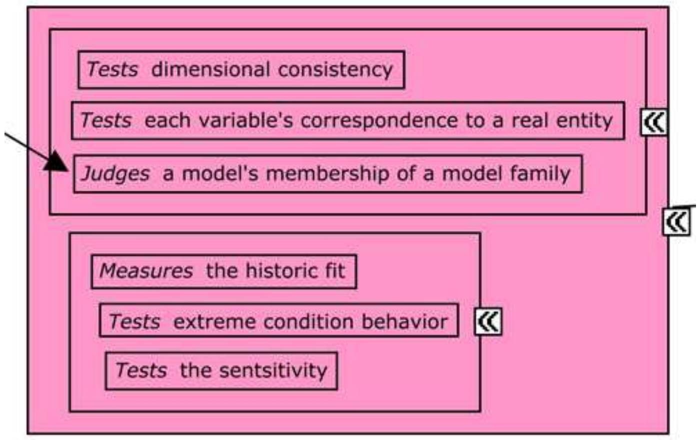


*Figure 9: Evaluating (the model)*

"Judging the validity of a simulation model" is evaluating, the next higher order level. It is illustrated in Figure 9. We find that the usual activities of structural and behavioral validation belong to this level and can be expressed as *testing*, *measuring* and *judging*. One might reflect on the role and the importance of validation in system dynamics education. We believe the subject belongs into any system dynamics course, but that it requires a fair deal of personal experience and perspective in the field; this is why in our concept map it depends on the entire system of lower level abilities and knowledge.

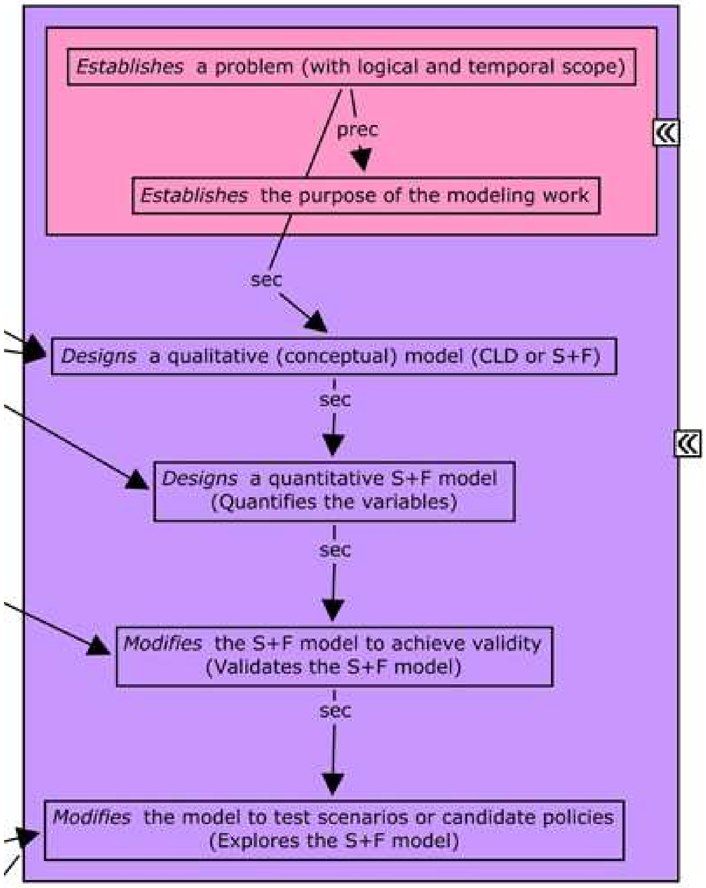


*Figure 10: Creating*

For the level "creating" we have chosen the label "developing modelling projects". This includes two activities belonging to "judging": *establishing* what the problem is and what the model's purpose will be. Following these initial activities, the model will be *designed* and *modified* during validation and exploitation. The "sequential" link indicates that there is a time order in which the activities are carried out. Of course, "modifying the model to achieve validity" connects to the group of abilities discussed around Figure 9, and "modifying the model to test scenarios and candidate policies" refers to what will now be introduced.

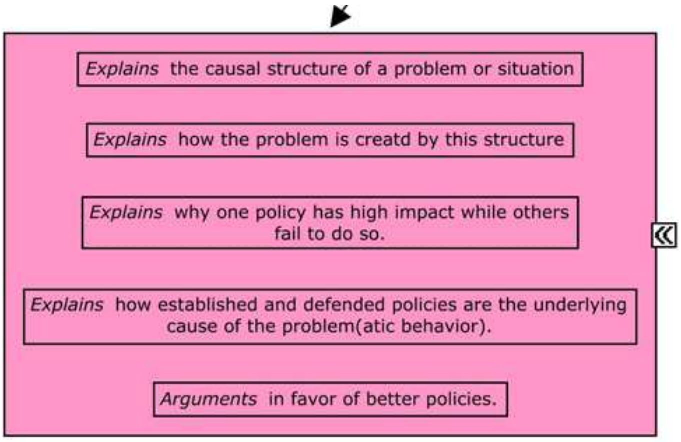


*Figure 11: Evaluating (policies)*

Arguable, "evaluating problems and decision policies" is what system dynamics strives for, and the development of simulation models in order to improve mental models is only an instrument for achieving this goal. Therefore, learners who demonstrate that they can *explain* the causal structure, the problem genesis and policies and who can *argument* for better policies fulfill what Forrester (2007) called for, which is certainly a satisfactory end point for a system dynamics course.

*Precedence relationship across the levels of the taxonomy*

As mentioned above, the visualization by level makes invisible the connections between elements belonging to different levels. However, these relationships are important aspects of the system laid out in the concept map.

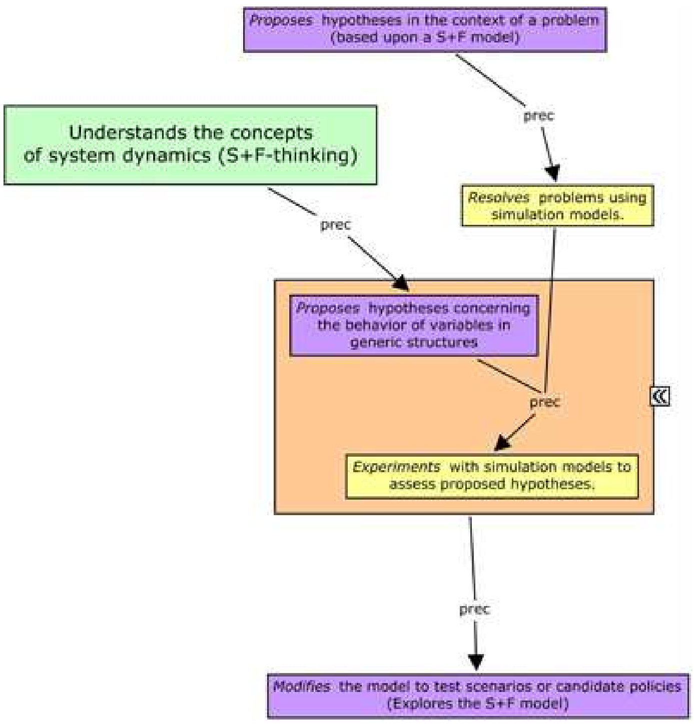


*Figure 12: "precedes" links (part 1)*

In Figure 12, it becomes particularly visible that some threads of learning evolve through the majority of levels of the taxonomy. This means that all the activities like "experiments with simulation models" reveal the degree to which a learner "understands the concepts of system dynamics". This is a challenge to learners and lecturers alike, since it means that one cannot pass a comprehension test and then move on to other issues: learners always have to demonstrate their understanding and lecturers always have to asses it.

In the following Figure 13, the uninterrupted chain of steps from the first *definitions* (that are memorized and recalled) to the high order activity of *designing* qualitative and quantitative models shows that there is, indeed, a logical order of progressing from simple tasks towards more complex ones, combining activities from virtually all levels of the taxonomy. Although the verbs evolve from *identify*, *define*, *describe* to *explain*, *predict*, *discover*, *experiment*, *test*, *judge* and *explain*, the objects remain the same.

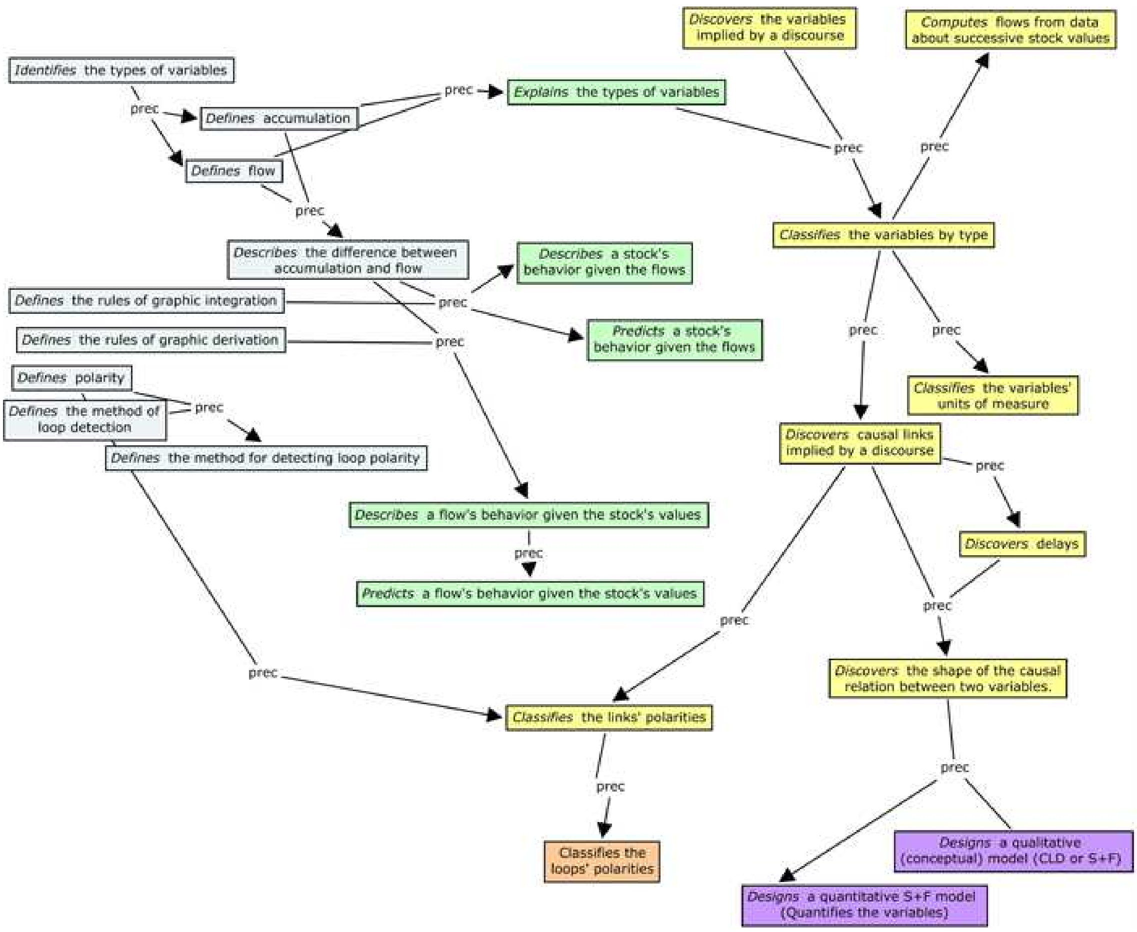


*Figure 13: "precedes" links (part 2)*

This concludes the presentation of our set of indicators for the learning of system dynamics.

## Discussion

*Using the competencies to plan and improve learning objects*

This system of indicators implies the set of internal resources that have to be put to work in system dynamics modelling. We believe it is practical to treat the group nodes of the map as "resources" and the detail nodes as "indicators".

It is then straightforward to use the resources and indicators to plan learning and assessment activities. In this, we assume that learning comes from personal activity; consequently, there must be a set of learning activities that cover the whole range of resources (with their indicators). Each learning activity will cover a certain set of indicators and the assessment of individual learning will cover these. Successful learning activities will yield high rates of achievement in the student groups, while low mean achievement will indicate that the respective learning activity should be revised or discarded. By following this logic of design -> implement -> assess -> revise, the set of learning activities and its respective objects (models, chapters and other objects) should be of high quality.

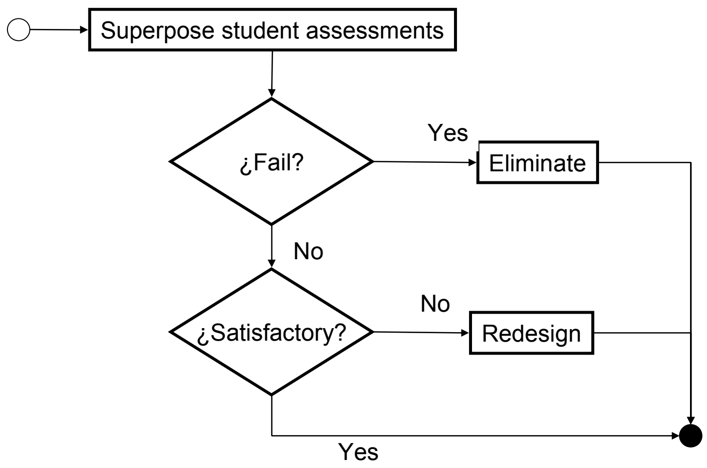


*Figure 14: activity improvement process*

The following figure contains a part of a planning grid where resources and indicators appear in rows and activities in columns. If an activity is to affect an indicator, the corresponding cell contains a 1 (otherwise it is empty). It is implied that each learning activity also contains an assessment of the learning achievements for each of the targeted indicators.

| System dynamics | Beer Game | Modeling to resolve problems | Introduction | Causality and feeback loops | Accumulatino and flow | Exponential behavior | Logarithmic behavior | S-shaped behavior | Growth and collapse | Delay and oscillation | Delays | Chains and co-flows | Model exploration | Guided modeling | Modeling |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **KNOWS SD modeling** | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **KNOWS SD concepts** | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Identifies generic behavior modes | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Describes generic behavior modes | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Identifies generic structures | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Describes generic structures | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| **UNDERSTANDS SD concepts** | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Associates generic behavior modes to generic structures | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Associates generic structures to generic behavior modes | | 1 | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |
| Interprets BOT graphs | | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | |

*Figure 15: an activity planning grid*

It is then possible that an indicator is targeted by more than one activity. The column sum is the number of items an activity attempts to cover, the row sum represents the number of learning activities that intend to trigger change in each indicator. It is easy to know if each of the indicators has been included in a sufficient number of learning activities, and one can distinguish smaller activities from larger ones.

Each activity can have a rubric with the specific indicators and different levels of performance. This facilitates detailed planning of the activities in its two components (learning and assessing). Also, the descriptive statistics of a student group's achievements in the indicators helps evaluating the activity; when used together with a minimum achievement threshold, one can immediately identify the activities which should be revised and improved.

Students may be assessed for a given indicator more than once; as mentioned above, since the topics learned earlier on are important for other topics, this is desirable. However, it makes necessary a rule for computing the profile for each student at a given point in time. If there have been *n* assessments, one could chose to consider only the most recent one, or a mobile mean. Additionally, the profiles recorded in the indicators of a given resource must be translated into a resource achievement profile – both topics are still under discussion.

| Student | Beer game | | Modeling to resolve problems | | Introduction | | Causality and feedback loops | | Accumulation and flows | | Exponentiql behavior | | Ligarithmic behavior | | S-shaped behavior | | Growth and collapse | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **KNOWS SD modeling** | X | | X | | X | 3,7 | X | | X | | X | | X | | X | | X | |
| **KNOWS SD concepts** | X | | X | 3,6 | X | | X | | X | 7 | X | 3,5 | X | 4 | X | 4,8 | X | 5 |
| Identifies generic behavior modes | | | 1 | 1 | | | | | | | 1 | 4 | 1 | 4 | 1 | 5 | 1 | 5 |
| Describes generic behavior modes | | | 1 | 1 | | | | | | | 1 | 3 | 1 | 4 | 1 | 5 | 1 | 5 |
| Identifies generic structures | | | 1 | 1 | | | | | | | 1 | 4 | 1 | 4 | 1 | 5 | 1 | 5 |
| Describes generic structures | | | 1 | | | | | | | | 1 | 3 | 1 | 4 | 1 | 4 | 1 | 5 |
| **UNDERSTANDS SD concepts** | X | | X | | X | | X | | X | | X | | X | | X | | X | |
| Associates generic behavior modes to generic structures | | | 1 | | | | | | | | 1 | 7 | 1 | 7 | 1 | 4 | 1 | 5 |
| Associates generic structures to generic behavior modes | | | 1 | | | | | | | | 1 | 7 | 1 | 7 | 1 | 4 | 1 | 6 |
| Interprets BOT graphs | | | 1 | | | | | | 1 | 7 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 6 |
| Describes a stock's behavior given the flows | | | 1 | 7 | | | | | 1 | 7 | 1 | | 1 | | 1 | | 1 | |
| Describes a flow's behavior given the stock's values | | | 1 | 7 | | | | | 1 | | 1 | | 1 | | 1 | | 1 | |
| Predicts a stock's behavior given the flows | | | 1 | 7 | | | | | | | 1 | | 1 | | 1 | | 1 | |
| Predicts a flow's behavior given the stock's values | | | 1 | 7 | | | | | | | 1 | | 1 | | 1 | | 1 | |

*Figure 16: Example of student monitoring sheet*

*Comparison with the systems thinking taxonomy*

As stated in the introduction, Stave and Hopper (2007) have developed a taxonomy for the case of *systems thinking*, aligned to Bloom's taxonomy. Their taxonomy contains many topics that are also part of the indicators in our work; however, many aspects of system dynamics go beyond systems thinking. Their taxonomy has not been conceived to serve for teaching system dynamics.

Still, the two taxonomies are useful for comparing systems thinking to system dynamics: in those aspects where systems thinking overlaps with system dynamics, the describing elements should be the same. Differences in grouping may be due to diverging theories of learning. While such a comparison would go beyond the scope of this paper, it is certainly a task that should be taken up in the future.

*What has been gained*

We believe that the concept map is not only practical for course planning and management, like shown in the previous subsection. It is also an explicit representation of what is learned, expressed in a widely used language (Bloom) and competency-oriented. This has several convenient consequences.

First, it allows lecturers to incorporate system dynamics in field-specific curricula and for learning activity and assessment planning. Other lecturers can more easily see what is learned in system dynamics, and if one develops similar concept maps of other competencies, it becomes easier to find points for connections.

Second, it allows students to know what is expected from them and take charge of their own process. This feature helps building a motivating work environment in which autonomy can be developed. Recall that – even though it has not been included in this concept map – the development of autonomy is one major aim of competency-based education.

Third, the concept map is not a definitive product. Just like system dynamics models are a momentary picture of one's understanding and part of an ongoing process of learning, this map is bound to be tried out and critique can be formulated to improve it. It may even be an opportunity to develop a shared understanding of what is being learned in system dynamics courses, and it may become the way we use to articulate a model of the stages of the learning process.

Fourth, the map can also be used to assess the degree to which each part of the map is covered by educational materials.

*For the future*

Naturally, the third and fourth points on the list above will be valid only if the map continues to be developed. We identify two immediate challenges. The first refers to consistency: Bloom artificially separates some activities ("is part of" links) and the assumed sequence over the 5 levels is not always sustainable. Even though it may be necessary to define levels and thus separate activities, the degree to which activities of different levels appear to belong together will require some research into the process of learning system dynamics. Hopefully, the fact of using a standard language will facilitate collaboration with educational researchers.

Second, there may be some degree of debate concerning the very map: naturally, we have taken design decisions and it may well be that there are alternative maps that can be developed to talk and think about learning system dynamics. In this sense, the community is invited to produce alternative maps, hopefully using Bloom's taxonomy. In that case, our work will be comparable and cumulative, and future comparisons will doubtlessly advance system dynamics teaching.

## Conclusions

This work has set out to develop a tool that would help to design courses and course modules for system dynamics in the context of competency-based education. In the absence of previous publications about the subject, it was decided to Bloom's taxonomy as a frame of reference (or language) for the development of a conceptual map showing what is learned and in which sequence.

The resulting map follows the taxonomy's sequence of levels whenever possible, but parts from it at several places. However, it is an explicit representation of the abilities a learner acquires and the conceptual objects that are manipulated in system dynamics. We have been able to derive a planning grid that allows to design learning and assessment activities and rubrics.

Even though this has been a step forward, this is work in progress. Several tensions between system dynamics and the taxonomy have to be overcome, and much work has to be done to advance in our understanding of the stages learners go through over time. Even so, we conclude this paper confident that it is a valuable step towards a contribution to the field.

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