Jl. of Computers in Mathematics and Science Teaching (2013) **32**(3), 303-320

Evaluating the Pedagogical Potential of Hybrid Models

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The paper examines how the use of hybrid models – that consist of the interacting continuous and discrete processes – may assist in teaching system thinking. We report an experiment in which undergraduate students were asked to choose between a hybrid and a continuous solution for a number of control problems. A correlation has been found between the preference of hybrid models and a low system thinking ability. We discuss the meaning of the results in terms of the state diagram notation, and link them with the new socio-technological reality created in the digital age.

"System approach" is a name for a collection of theories and methodologies studying complex phenomena (Wiener, 1948; Ashby, 1956; Bertalanffy, 1968). "System dynamics" is a methodological expression of that approach, using computerized models to manage and control behavior of systems (Forrest, 1961; Forrester, 1968; Senge, 1990; Sterman, 2000). Besides its use in research and management, system dynamics has been widely applied for educational purposes. Incorporating constructivist learning principles (Piaget, 1971), system dynamics have been used as a cross-discipline subject in k-12 schools, colleges and universities, and in manager education programs (Forrester, 1994; Sterman, 1992; Richardson, 1996; Saeed, 1997).

The main goal of system dynamics education is to develop system thinking skills (Forrester, 1994; Richmond, 1993; Frank, 1999). The importance of teaching such skills is widely recognized by educators in various fields of science and engineering education (Ben-Zvi-Assaraf and Orion, 2010). However, despite the considerable activity in teaching by using the system dynamics methodology, there is still little scientific support for the actual value of the methodology (Sterman, 2000). Furthermore, research has shown that even highly educated university students – some of them with background in science and engineering – encounter difficulties in understanding basic concepts of system dynamics (Seeney and Sterman, 2000, 2002; Kainz and Ossimitz, 2002; Jensen and Brehmer, 2003; Cronin and Gonzalez, 2007; Cronin et al., 2009; Sterman, 2010).

Our previous study has demonstrated a way to simplify the method of system dynamics by changing the structure of the models it uses (Levin et al, 2001; Levin & Levin, 2002; Levin & Levin, 2012). Namely, it was suggested that learning might be affected if the standard continuous models, commonly used by system dynamics, are replaced with so-called hybrid models. The hybrid models are based on interaction between the continuous dynamics and the discrete dynamics (see below). It has been argued that hybrid structures offer a more intuitive way of modeling, and may assist in teaching some basic system thinking concepts.

Description of Hybrid Models

Hybrid models describe systems where continuous and discrete subsystems interact (Branicky, 1995; Mahler, 2001). In the context of control theory, a hybrid model is composed from two distinct sub-models: a digital discrete unit of control, and a continuous element representing a physical or technological process (Johansson, 2000). These hybrid models have vast applications in computer embedded systems, and in recent years have been much developed, both in theory and in practice.

The hybrid system consists of a two-level structure (Figure 1). On the lower level, differential equations modeled as stock-flow diagrams form a continuous system. On the higher level, logical functions, modeled as a finite state machine (FSM), constitute the discrete part (Levin & Levin, 2002). The two levels are connected through a two-way channel of communication: a binary vector of information $(x_1, \ldots, x_L)$ is sent from the continuous to the discrete part, and a binary vector of instructions $(y_1, \ldots, y_L)$ is sent in the opposite direction.

For educational purposes, we suggested to use the stock-flow representation to model the continuous part, which is widely used by the system dynamics community (Sterman, 2000). State diagrams can be used to model the behavior of the Finite State Machine (FSM) in the discrete element.

Several examples for implementation of such architecture in educational contexts were demonstrated in a previous study (Levin et al, 2001; Levin & Levin, 2002).

Hybrid models provide reasonable approximation to continuous models and are a "tradeoff between real-world relevance and model complexity" (Maler, 2001; Levin & Levin, 2012). Unlike their equivalent continues models – which are composed on one level of stock-flow relations - the hybrid models have an hierarchical structure, which divides the system into smaller components, and enables modularity in the constructing of the models. Benze and Franklin (1995) described three stages for designing a hybrid model:

(a) Designing the controlled process as a stock-flow diagram
(b) Designing the digital controller as a state diagram
(c) Exploring the models by changing values of the connecting vectors

This hybrid model methodology enables flexibility in the learning process. Students may be instructed to design only the digital controller to a given continuous process, or vice versa. It also enables various modes of interaction when using computer simulation (Alessi, 2000). For example, it is possible to combine an analytic study of the behavior of the continuous process using the simulation tools, with a synthetic design of the digital controller. Such integration of analytic and synthetic styles of thinking develops the awareness to their possible combination and collaboration in the system design (Levin and Lieberman, 2000).

Research Rational

The current study is an empirical test to evaluate how the use of hybrid models may affect teaching. It extends the current research on system education by studying the pedagogical implications of introducing a new method of modeling. Being pioneering in its field, the study is designed to measure a potential value - rather than an actual value - of hybrid models in education. The actual value would have best been tested using a pretest-posttest design. To measure the potential value, we look for correlations between the hybrid models and ordinary modes of thinking.

The potential value of the hybrid models is measured relatively to that of equivalent continuous models. The hierarchical structure of the hybrid models allows separating the control element from the controlled process in both the hybrid and the continuous models. Thus the difference between the hybrid and the continuous models is presented as a difference between control solutions. Given continuous process and a control task, participants of the test are asked to choose between discrete and continuous control solutions, based on several criteria.

To determine the reasons for the choices, we look for correlations between the preferred solution and other variables, in particular the variables of academic background and system thinking skills. By doing so, we try to establish connections between the preferred solution and intuitive mental models of the participants. Our attitude is based on a pragmatic theory of truth (James, 1907). We assume the choice of the model is partly caused by the will to believe in it, and that the weight of this subjective factor is affected by the level of understanding and the academic background. When holistic intuition replaces analytical thinking, the reasoning is vastly determined by existing mental models.

The improvement of existing mental models is a key goal in the system dynamics education (Doyle and Ford, 1998). Mental models are primitive representations of reality, which guides us in our thinking and decision making (Forrester, 1971). Their modification is essential to improve system thinking, and can be achieved through their activation during the learning process (Senge, 1990). In the process of model construction, hidden mental models become explicit, and may be explored critically through discussion and computer simulation.

To evaluate the pedagogical potential of hybrid models, the study looks into ways mental models are applied in the context of problem solving. The more the learning is relevant to intuitive models of thought, the more it will be affective as an educational process.

Research Questions

The experiment is designed to answer two research questions:

1. To what extend do students prefer hybrid solutions over continuums solutions?
2. How is the preference correlated with academic background and dynamic thinking ability?

We measure the "system thinking ability" by asking questions concerning the dynamics of the continuous processes, before the control solutions are presented. The questions are based on previous research for measuring system thinking ability, which have been conducted by members of the system dynamics community (Sweeney and Sterman 2000; Kainz and Ossimitz 2002). Further details are given in the methodology section.

METHODOLOGY

We presented to university students questionnaires describing three control assignments. The students were asked several questions to test their understanding of the dynamics in each case, and were instructed to choose between two control strategies. Statistical tests were used to analyze the answers, and look for correlation between the choices, the ability to understand dynamics and the academic background. Details of the procedure are given below.

Subjects

One hundred and twenty one undergraduate students from the Tel Aviv University participated in the study. The students had no prior formal experience in learning the system approach.

Fifty-nine of them were natural sciences and engineering students (49%), and sixty two were social science students (51%); 36% were first year students, 43% were second year students, 16% were third year, and the rest were in their fourth year in the university.

49% of the participants were females, and 51% were males. The younger participant was 19 years old, and the older was 30. Nearly a quarter were between age 19 and 22, 64% were 23-26, and 13% were 27-30.

Data Collection and Analysis

We approached the students around the campus and distributed the questionnaires. The students were asked to fill the questionnaire on their free time, and to call us when finished. Most students called us within 24 hours, and 6% did not return it due to various reasons. When collecting the questionnaire we paid them the equivalent of 8$.

The majority of the students (approximately 90%) were interviewed on returning the questionnaires, and confirmed they have answered the questions alone. Their answers have been recorded in writing. They were then given a chance to change their choices, which they rarely did (less than 3%).

All 121 participants answered all the questions in the questionnaires. The results were coded to a spreadsheet, and then transformed to SPSS software for statistical analysis.

Questionnaire

We presented the subject with three stories describing a dynamic process. The stories were taken from different worlds of content, and were given in a random order. The First described a change in population of rabbits. The second describes a change in the amount of money in a bank account. The third described a change in the temperature of a room. An example of one of the stories from the questionnaire is given in Figure 2.

The type of dynamic behavior in each case is unique. The first described an exponential change. The second described a logarithmic change. And the third described sequences of linear changes.

For each case, a control task was given. One task was determining a hunting policy to keep the size of the population of rabbits in a certain range. Another task was deciding on an investment policy to maximize the savings in a bank account. The third one was choosing a control policy for an air-conditioner to keep the temperature of a room around a certain value.

Table 1
Input and Output for the Controlling Element

Output	Input	Case
Number of hunters permitted	Number of rabbits	Rabbits
Sum deposited for saving	Sum of money in the account	Bank
Volume of heater	Room temperature	Room

The participants were asked several questions to measure their dynamic understating ability, and were then asked to choose between two strategies of control, based on several criteria.

Questions Measuring System Thinking Ability

For each story, four questions were given, addressing the dynamic behavior of the process. These questions are used to measure the system thinking ability of the participants, and are based on questions given in prior research (Sweeney and Sterman 2000; Kainz and Ossimitz 2002). The main difference between our test and those mentioned is a closed multiple-choice structure of the answers as compared to open answers. There were three possible answers per question, with only one correct answer. The distractors are based on common mistakes exposed by the previous researches.

Questions on Control Strategies

For each control task, two solutions of control were presented. One was of a discrete nature, and the other continuous. Taken as one system with the continuous controlled process, they are referred to as the hybrid solution and the continuous solution. Both the solutions offer a satisfactory result for the control task. Two experts secured their validity in terms of correctness and equivalence.

We asked the participants to choose between the controls solutions in several criteria:

- Optimality: Which solution yields better results for the control task?
- Compliance: Which of the solutions meets the minimal requirements of the task?
- Friendliness: Which solution is friendlier to use?
- Recommendation: Which of the solution would you recommend?
- Changing Values: Which of the solution would you recommend if a change in numerical values is allowed?

The options were either the hybrid or continuous solutions, or both of them as equally good.

Reliability and Validity

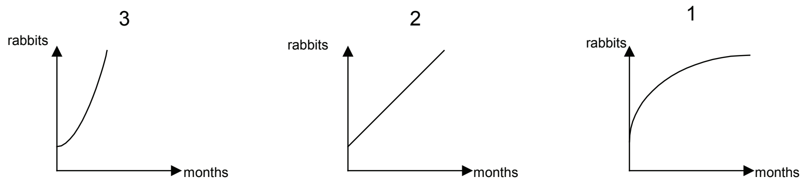
A pilot test was given to ensure that students understand the questions correctly. After the pilot test we have made several changes, especially in the wording and graphical presentation of the answers.

Two experts secured the validity of the questions in terms of correctness and equivalence of control solutions. The case studies in the questionnaire were given in random orders, while the questions, in each case study, were in a fixed order to keep the inner logic consistency. The results were tested for inner consistency as will be shown below.

RABBITS POPULATION DYNAMICS

The reproductive rate of rabbits living in a natural park is 10% of the population size per month. The births are evenly distributed throughout the days of the month. The mortality rate is 5% of the population per month. The deaths are also evenly distributed through the month.

1. *How does the rabbits population change over time?*
   - a. *Grow in increasing speed*
   - b. *Grow in declining speed*
   - c. *Grow in a constant speed*
2. *Which of the following graphs best describes the growth in the rabbits population over* time ?



On hunting seasons the mortality rate jumps to 15% per month, while the reproductive rate stays 10% as before.

3. How does the rabbit's population change over time on hunting seasons?
   - a) Decline in constant speed
   - b) Decline in declining speed
   - c) Decline in increasing speed
4. Which of the following graphs best describe the change in the rabbits population on hunting seasons?

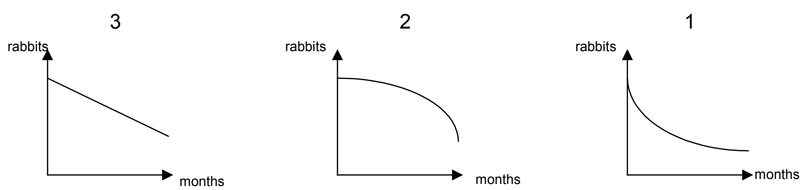
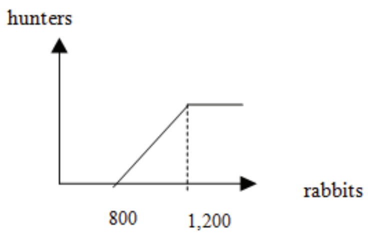


Figure 2. An example of a story from the questionnaire.

The park inspectors recieve daily data on the number of rabbits from a system of sensors. The ideal number of rabbits to maintain equilibrium in the park is 1,000. Any number between 700 and 1,300 is ok. If the number is above or below these values, there is an environmental risk.
The inspectors grant hunting permissions on a daily basis. When hunting is free for all, the mortality rate of rabbits reaches 15%. When it is totally forbidden, the mortality rate drops to 5%. The reproductive rate stays always 10%.
Two options for a hunting policy were presented to the inspectors:

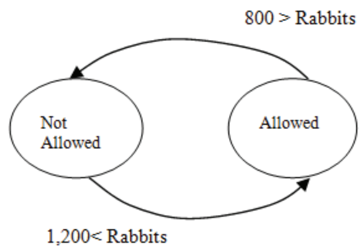
Gradual Policy

When the number of rabbits exceeds 800, allow hunting gradually. The number of hunters will grow in proportion to the number of rabbits. When the number of rabbits exceeds 1,200, hunting is free.



Two States Policy

When the number of rabbits exceeds 1,200, allow free hunting.
When the number of rabbits drops below 800, prohibit hunting.



Which of the policies will secure the number of rabbits within the safe limits?

a) gradual policy b) two states policy c(both

Which of the policies will keep the number of rabbits closer to the ideal state (1,000)?

a) gradual policy b) two states policy c(both

Which of the policies is simpler to implement?

a) gradual policy b) two states policy c(both

Which policy would you recommend?

a) gradual policy b) two states policy c(both

If you could change the numerical values, which policy will you recommend?

a) gradual policy b) two states policy c(both

Figure 2 continued.

RESULTS

Ability to Understand Dynamics

They were 12 questions to measure the dynamic understanding ability of the participants. The correct answer to a question was awarded 1 point, and incorrect answers - 0 point. The reliability factor of this part of the test was Alpha=0.69. The average score was 71 with SD=0.2.

22% of the students scored more than 80 points. 31% failed with less the 60. The question with the best scores got 89% correct answers. The worst result per question was 37% correct answers. The variance of the average is 0.72, while the variance of details is 0.18.

Hybrid vs. Continuous Solutions

The preference of control strategy was measured on a scale from 0 to 1, where 0 represents favoring of the discrete logical control strategy (hybrid model), 1 represents favoring of the continuous control strategy, and 0.5 means that both of them are the same for a participant.

In general, the students preferred the continuous type of control, with a value of 0.56. An inner consistency test yields a sufficient value of Alfa Cronbach, = 0.72. The continuous approach was conceived much better in terms of optimality recommendation. The students considered both strategies as nearly equal in terms of compliance with the requirements, while the hybrid approach was considered friendlier to use.

Table 2
Hybrid vs. Continuous Control Solution

Standard deviation	Degree of preference*	Criterion
0.18	0.56	General
0.23	0.72	Optimality
0.24	0.51	Compliance
0.25	0.35	Friendliness
0.30	0.59	Recommended
0.29	0.61	Changing Values

* 0 represents absolute preference of hybrid approach.
1 represents absolute preference of continuous approach.

Difference by Story

There was a significant difference of results between the stories. The dynamic understanding ability was much lower in the story of the population of rabbits, compared to the two other stories. The rabbits story was also the only one were the hybrid control strategy was preferred. Table 3 gives the numbers, based on a standard statistical test.

Table 3
Results by Story

Hybrid vs. continuous control solution	Dynamic thinking ability	
0.45	50	Rabbits
0.57	82	Bank
0.65	80	Room

Influence of background

A correlation has been found between the background of the students and their preferred modeling approach:

1. Students with relatively low dynamic thinking ability tend to prefer the hybrid type of modeling. Students with relatively high dynamic thinking ability tend to prefer the continuous type of solution.
2. Social sciences students prefer the hybrid approach more than natural science and engineering students.

The regression analysis yields a total value of R square= 0.14(Sign F> 0.001). That means that the linear dependence of the dependent variable on the independent ones explains 14% of its variation. In other words, it provides a partial explanation to the behavior of the variable. Table 4 shows the proportional contribution of each of the independent variables to the variation in the preference of the control type. It shows that the relative contribution of the thinking ability and faculty is more or less the same.

Table 4
Results of Regression Analysis

Variable	Relative weight Beta	Correlation with preferring hybrid vs. continuous solution	Reliability by T-Test
Dynamic thinking ability	0.18	0.25	0.002
Faculty	0.18	0.24	0.003

DISCUSSION

The results show that the majority of students preferred the continuous solution over the hybrid one for a number of control tasks. This is not surprising, for it was rightly conceived by the students as a more optimal solution. From the mathematical point of view, the continuous solution was indeed better.

Nevertheless, despite its objective inferiority, the hybrid solution got a 44% support. Analysis of the affecting variables reveals that the selection of the hybrid solution is correlated with relatively low understanding of the problem. The hybrid solution was favored more by the students from the social sciences and humanities, whose mathematical skills are less developed. The only story in which the hybrid solution got better scores – the one on rabbit population – was also the story were the scores of dynamic understanding were the lowest.

The correlation between low understanding and hybrid models preference may be explained by the relatively simplicity of such models, and by their similarity to common intuitive mental models. However, this explanation needs further clarification, as it contradicts the legacy of experienced system dynamics educators (Forrester, 1961; Sterman, 2000). Forrester and Sterman argue that conditional propositions such as if-then-else are harder for comprehension when compared to continuous control. Therefore the apparent intuitiveness of the hybrid models may be less connected with the logic, and more with the state diagrams notation used in our case.

State Diagrams

Maj and Veal (2007) demonstrated advantages of state diagrams as a pedagogical tool in the engineering education. Talis (2002) argued that state diagrams support a declarative mode of thinking, which may be favored by students who tend to use intuitive rather than analytic reasoning. The formal notation of a 'state' resembles the psychological 'state of mind' that leads to an action. It provides a trustworthy pictorial presentation to the way the conditional logic "if A then B" is used pragmatically in the natural language.

The familiar associations of the state diagram partly explain why the hybrid solution was considered friendlier than the continuous one. The operational description of friendliness in the questionnaire may easily be interpreted as 'familiar'. It was described as "simple to use and follow" in the stories on the rabbits population and the bank account. In the story on the air conditioning it was described as "pleasant"' which may be identified with a familiar sensation of change.

However, the attitude towards state diagrams should be tested in more complicated cases. The two states' diagram in the current study is the simplest diagram possible; and more complicated logic poses much greater challenges. We have shown examples of integrating a three states' diagram and a four states' diagram within a hybrid model (Levin & Levin, 2003). Further research should test whether the apparent intuitiveness of the hybrid models is maintained with the rise of complexity.

Even when starting with a two states diagram, the hierarchical structure of the hybrid model enables gradual growth in several directions. Further enriching the control unit is achieved by either adding more states, or changing the vector connected to the continuous process, or transforming the controller to an equivalent continuous element. The modularity of the hybrid models enables variety of possibilities for advancing in complexity (Levin & Levin, 20002).

Gradual construction of models is a common method when exploring complex systems (Sterman, 2000). In the system dynamics tradition (continuous approach), students start with few variables and feedback loops, and gradually add more of them to make the model more realistic. The problem with this approach is that you get more of the same, and it may therefore be tiresome and boring. In this sense, hybrid models provide more pedagogical variety. Starting with a simple two states diagram, it enables several possibilities of development towards more realistic models.

Moral Considerations

Another issue is more speculative in nature, and yet may be implicated by the results. The choice of the participants seems also to be affected by moral considerations. Several participants told us in the interviews, upon returning the questionnaires, that they preferred the hybrid solution because it seemed to them less harmful to the rabbits. Some of them even described their decision in terms of "moral choice". Objectively, their reasoning is wrong. The discrete control is not better than the continuous one, in terms of preserving animal rights. But the students seemed to rely on intuitive reasoning rather than on analytic one, and preferred a style of idealistic thinking over realistic cold calculations.

We assume that the moral element in the question encouraged the students to apply an archaic mental model, rather than to use some analytic reasoning. The psychological dynamics follows a classical pattern of regression (Freud, 1917). The moral content, which derives from the demand to set a hunting policy, causes anxiety. Under stress, fixation of archaic models usually replaces high level sophisticated thinking. The fixation creates more anxiety, which blocks critical thinking and reflection. Under moral pressure, avoiding the risk of a mistake is considered more important than choosing the best solution (Kahneman, Slovic & Tversky, 1982). Old and familiar modes of thought are considered good choice for playing safe.

The mental models corresponding to the discussed hybrid solution resemble early stages in the construction of morality of a child (Piaget, 1971). Piaget argued that through interaction with the expectation of his environment, the child develops a primitive morality as a mode of self control. The guiding rules for the child behavior resemble the logic of a state machine. In response to reality, he is either in a state of "allowed" or in a state of "not allowed". In other words, logical control may be a tacit knowledge that is constructed in early stages of the development of morality (Polanyi, 1964).

The hierarchical structure of the hybrid model - which divides between the process and the control element – also contributes to the discrete mode of reasoning. By separating the logical controller from the natural process, it emphasizes the difference between moral values and scientific facts. The separation of values from facts leads to the idealistic moral reasoning, which differs from the naturalistic approach of the system dynamics towards moral questions. The continuous modeling views decision rules as continuous variables within the model, barely unlike the variables describing factual processes (Forrester, 1998).

The difference between the attitudes is a matter of resolution. The continuous approach looks at reality from 10,000 foot, while the hybrid approach is near the ground level (Richmond, 2001). The high perspective sees decisions as human attitudes, which are part of a social and psychological dynamics. From the point of view of an individual, decisions are experienced as a product of reasoning, thus obeying discrete logic.

The coexistence of different perspectives on one subject is common practice in the constructivist learning (Piaget, 1971; Papert, 1980). A dialectic shift between perspectives leads to a balanced view concerning the nature of decisions. The idea that decisions both affect and are affected by social processes is central to the system approach. Awareness of the mutual dependence serves one of the main goals of the system education: to develop individual responsibility for the future of the environment in which we live (Forrester, 1994).

Modifying the Continuous Paradigm

The study points to a certain similarity between simple hybrid structures and common mental models. It is yet unclear whether such correlation will persist with more complicated models. But complex hybrid models have another advantage in the system education, as they resemble an emerging archetype of real systems. The spread of digital devices, combined with continuous social processes, create a hybrid environment. Nowadays, the human daily experience is very much divided between a digital virtual world and an actual analogue world.

The emerging hybrid reality poses a challenge to the system dynamics education, which belongs to a long tradition of continuous modeling. The historical roots of this tradition can be traced to the beginning of modern science (as taught by Richardson, 1991; Sterman, 2000). Starting with the birth of the modern physics in the 18 century, the great success of models based on infinitesimal calculus led to the belief that continuous modeling is the only language to natural world (Bunge, 1974). From the physical sciences, these models rolled to the classical control theory and further to descriptions of social changes (Richardson, 1991). According to this tradition, discrete events and local decisions are no more than insignificant details on the surface of deep continuous processes (Forrester, 1961; Forrester, 1968; Senge, 1990).

The continuous paradigm has already been challenged in various fields of science and engineering. Computer science emerged as an independent discipline, based mostly on the discrete style of thought (Harel, 1993). The control theory has also been transformed, as sophisticated mathematical models set the foundation to digital control (Dorf & Bishop, 2001). A growing number of science and engineering students learn courses on logic control and algorithms, while the general public understands basic discrete concepts from their interaction with digital devices. We believe that these changes should lead to some modification in the system education.

The hybrid approach adds a digital dimension to the continuous paradigm, while retaining its basic philosophy concerning natural and social processes. Therefore the introduction of hybrid models should not be conceived as a revolution in the system education, but as a natural evolution required for adaptation to a changing reality.

Limitations of the Study

Being a pioneer study on hybrid models in education, the research has some limitations. The models were relatively simple. The participants were a homogenous sample of students. Their task was to choose between control solutions, and to answer questions of understanding. They did not construct their own models, nor explored computer simulations with running data, though these activities are common practice in system dynamics education. Further research should aim at improving both the type of models used, and the methodology for interacting with them.

Conclusions

The study examined how the use of hybrid models may assist in developing system thinking skills. We reported an experiment in which undergraduate students were asked to choose between a hybrid and a continuous solution for a number of control problems. The results showed a correlation between low understanding and hybrid models preference. The correlation may be partly explained by the relatively simplicity of such models, and by their similarity to common intuitive mental models. Further research is required to develop a hybrid methodology for modeling, and to explore specific contexts for use in education.

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