A test of the relative effectiveness of using systems simulations to increase student understanding of environmental issues

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Abstract

This paper reports on an experimental study testing the relative effect of using simulation models on systems thinking in a college-level Introduction to Environmental Science section. The preliminary findings show mixed results. It is unclear whether this is a result on the systems simulations used in the interventions or the assessment techniques employed to study their effectiveness.

Key words: education, environmental science

Introduction

Educators in the system dynamics community have long supported the notion that systems thinking skills are an essential part of education. Systems-oriented education gives “student s a more effective way of interpreting the world around them” (Forrester, 2009). Systems-oriented education supports active learning (Grant, 1997). Diana Fisher states that in her classroom experience “students learn effectively when they are actively engaged in building skill when working with abstract concepts”(2008:1) Research supports active versus passive learning in increasing student motivation (Cherney, 2008). Students involved in active learning techniques have also demonstrated greater retention of course material (Benware and Deci, 1984). System dynamicists agree that systems thinking skills increase understanding of complex problems (Maani and Maharaj, 2004). This is particularly useful in environmental education as environmental systems are very complex and often produce results that are difficult to predict (Grant, 1998).

Although systems dynamicists agree that systems thinking skills are effective in tackling complex problems, few studies give quantitative evidence of the effectiveness of systems interventions (Doyle, Radzicki and Trees, 1998). In Doyle’s words, “there is insufficient evidence to convince skeptical, scientifically minded observers, which is crucial if systems thinking ideas and techniques are to become more widely accepted in educational and corporate settings"(1998:254). A larger base of empirical evidence supporting systems thinking as a tool to increase understanding of complex issues is crucial to developing effective interventions.

This paper reports on an experimental study testing the relative effect of using simulation models on systems thinking in a college-level Introduction to Environmental Science section.

Problem Statement/Research Question:

Researchers have studied systems thinking and system dynamics in various classroom settings. Hopper and Stave (2008) identified fourteen studies that tested systems thinking interventions in the classroom, from kindergarten to the postgraduate level. Most of the studies evaluated students' ability to understand dynamic behavior and their ability to differentiate types of variables and flows. Both of these are intermediate systems thinking skills, as described in Stave and Hopper's proposed systems thinking taxonomy (2007). Very few studies examined the lower level skills of the systems thinking taxonomy.

The purpose of this study was to test the effect of using systems simulations on students' systemic understanding of environmental issues in an introductory environmental science course. This research supports two goals. One is to develop better tools for increasing systems thinking skills through the use of simulations. The other is to improve methods for assessing a change in systems thinking capabilities.

We asked the question: Does the use of systems simulations in an introductory environmental science course affect the students' systemic understanding of environmental issues? Another question that emerged in developing the study was: Are current methods of assessment effective in measuring a change in systems thinking abilities?

Hypothesis:

Our hypothesis at the outset of the study was that the students that used systems simulations in conjunction with lecture material would demonstrate greater systemic understanding of environmental issues than the students that were enrolled in the lecture-only section.

Method

The study was conducted on about 209 students enrolled in four sections of an Introduction to Environmental Science course in the spring of 2009. Demographic data shows that students in all four sections were similar in age distribution, environmental education level and motivation for taking the class.

The four sections were live lecture classes. Class size varied. The classes had 51 students, 107 students, 52 students and 89 students. At the beginning of the semester, two sections were chosen at random to be the experimental sections. The other two sections were the control sections. The experimental section had 107 students and 89 students.

All four sections had five main educational components: assigned text book readings, lecture material, five assignments based on the readings and lecture, and four quizzes, and a final, comprehensive quiz at the end of the semester. The experimental sections used systems simulations to complete three of five assignments about an environmental issue presented in class. The control sections completed the same assignments, but with only a text description of the issue.

Course lecture material was based on an introductory text book and covers a variety of topics in the environmental sciences. The text and lectures paid close attention to the human relationship with the environment and particularly to how human activities impact the natural world and what services are provided to human beings from the natural world. All sections had the same text book.

All sections were team-taught by three instructors, but all received the chapter's lecture from the same instructor.

Assignments:

The five assignments were designed for students to consider their role in environmental issues. Of the five assignments, three used a systems simulation to enhance lessons taught in class. For those three assignments, the experimental sections used the simulations to complete questions about the environmental issue covered. The control sections were given an equivalent text description of the issue and asked to answer the same questions. Table 1 describes the five assignments and what kind of simulation was used.

Table 1: Description of simulations used for each class assignment

Assignment	Simulation used
1: Students watched a video about the ecological footprint and the used a web-based calculator to calculate their own.	Web-based ecological footprint calculator with graphics
2: Students were asked to describe the effect on total population when the number of births and number of deaths in a population are increased or decreased.	An original model was created with total population as the stock and number of births and number of deaths as the inflow and outflow.
3: Students were asked to manage a herd of reindeer so that the lichen that is their primary food source is not overgrazed.	Sawicka and Kopainsky's (2008) model of reindeer herd/lichen dynamics gives student a tutorial on how to manage the reindeer herd and instructs them to decide on herd size every year for fifteen years to maintain lichen growth at an optimum for their survival.
4: Students were asked to test out carbon emissions levels and note the effect on CO2 in the atmosphere.	Sterman's (2006) bathtub model allows students to increase and decrease carbon dioxide emissions. The output graph simulates atmospheric CO2 levels over time. Computer graphics depict rising level in a bathtub, representing rising carbon dioxide level in the atmosphere.
5: The Story of Stuff video and reflection	None

We focused on Assignments 2 and 4 for this study. Systems underlying the simulations used in these two assignments were similar in structure. Assignment 2, Population Dynamics and Assignment 4, Carbon in the Atmosphere, used one-stock, two-flow systems to explain the concept of accumulation. We were able to assess the same systems thinking skills, asking similar questions in different contexts.

*Assessments***:**

Students were given a baseline assessment, four quizzes and a final exam. Each quiz contained about 20 questions that were either multiple choice or short answer. Multiple choice questions were either a question to be answered or a prompt to be completed. Five answer options were given with one clear, correct answer. Short answer questions asked the students to describe a concept in a few sentences.

Questions on the baseline assessment and the final exam were used as pre- and post test measures of systems thinking skills. The questions assessed students' ability to recognize interconnections, differentiate between stocks and flows and understand the way something in the system accumulates. The questions focused on assessing these abilities in the context of the topics covered in the assignments.

The first question focused on population change and was a short answer question. The question used a graph of total population, birth rate and death rate through four socio-economic stages: pre-industrial, transitional, industrial and post-industrial. In the pre-industrial stage birth rate and death rate are both relatively high and stable, causing total population to remain relatively low and stable. In the transitional phase, death rate drops, while birth rate remains high, causing total population to increase. During the industrial stage birth rate drops to a level just above death rate and total population continues to increase, but at a slower rate. In the post-industrial stage, birth rate drops below death rate and there is a decrease in total population. Students were asked why, if birth rate is falling in stage 3 (the industrial stage), population is still increasing? The correct answer would state that the reason total population decreases is because birth rate is still less than death rate.

A multiple choice question asked students to complete the phrase, "To reduce the amount of greenhouse gas in the atmosphere, we need to…" Five answer options were given:

a. Reduce the amount we add to the atmosphere each year by only 10 percent.
b. Do nothing; the level of greenhouse gases in the atmosphere is decreasing naturally.
c. Make sure the amount added to the atmosphere is less than the amount that is removed.
d. It is not possible to reduce the amount of greenhouse gases in the atmosphere.
e. None of the above.

The correct answer is c. Make sure the amount added to the atmosphere is less than the amount that is removed.

The final exam also included a diagram with one inflow, one outflow and one stock. There were three questions associated with this diagram. Two multiple choice questions asked students to identify the inflow/outflow conditions necessary for the stock to increase and decrease. The last questions asked students to explain, based on the given framework, what would have to be true of emissions and removal in order for carbon in the atmosphere to decrease.

Table 2-Systems-oriented assignments and what skills they test

Assignment	Task in assignment	Systems thinking skill assessed in quiz
2: Population dynamics	Students were asked to identify the correct trend, out of four options, for total population change over time for a given rate of 'number of births' and 'number of deaths.' Model users were then instructed to simulate each condition with a model provided online and comment on the results.	-Recognizing interconnections -Identifying stocks and flows. -Understanding accumulation.
4: Climate change	Models section students were directed to The Climate Bathtub Animation. They completed the model activity online, and then were asked to reflect on carbon emissions, absorption and their relationship to carbon dioxide levels in the atmosphere. They were also asked what would have to be true for carbon dioxide levels in the atmosphere to decrease.	-Recognizing interconnections -Understanding stocks and flows. -Understanding accumulation.

Evaluation

Each question was evaluated to determine which systems thinking skills it assessed, that is, which systems thinking skill would be demonstrated in a perfect answer.

Booth Sweeney and Sterman scored participant understanding of systems concepts on five levels for open-ended, interview questions (2007). Following this model students' answers were given a score of 0, 1, 2, 3 or 4, based on the systems thinking skills demonstrated in their answer. The previous study coded answers based on a full range of systems thinking abilities. Our study focused on only the most basic skills. The four tiers of understanding are based on the four systems skills established at the beginning of the study: no systems understanding, recognizing interconnections, understanding stocks and flows and understanding accumulation.

No answer or an answer of 'I don't know' received a Level 0 score. Level 0 was also assigned to answers that did not recognize any interconnection or influence of one part of the system in question to another.

The first level of systems thinking is recognizing interconnections. If an answer demonstrated this skill, it was assigned a value of 1. Examples of phrases that indicated a student's ability to recognize interconnections are "A causes B," or "If X, then Y," "A change in A causes a change in B." The interconnections identified did not have to relate stocks and flows in the system. For example, carbon in the atmosphere increases when carbon emissions are greater than carbon removal, however students would often describe a change in carbon in the atmosphere in terms of human activity that contributes to carbon emissions. An example would be “Too many cars on the road increase carbon in the atmosphere.” This student understands a causal connection, but has not proved that they know the structure of the system.

The second level of systems thinking is understanding stocks and flows. An answer was assigned a value of 2 if it demonstrated the students’ understanding that one type of variable causes something to accumulate and one type of variable accumulates. Answers that demonstrate this ability might describe one variable as adding to another. An example answer for the population activity is “a high birth rate causes total population to increase.” This student recognizes which variable is a flow and which variable is a stock and recognizes the casual relationship between the two.

The third level of systems thinking is understanding accumulation. The mechanism may be different for different system structures. The systems underlying the simulations in this study have one inflow and one outflow. In order to understand how the stock in that system accumulates, the student must understand how each part of the system relates to the others. An example answer, using carbon in the atmosphere, would be “Carbon emissions must be greater than carbon removal in order for carbon in the atmosphere to increase.”

Multiple choice questions were evaluated as correct or incorrect. If the student answered the question correctly, they demonstrated the systems thinking ability assessed by that question.

Short answer questions asked students to explain a concept. For each question, a perfect answer required the ability to recognize interconnections, understand stocks and flows and understand accumulation. Answers were scored based on the systems thinking skills they demonstrated.

We compared average pre-test and post-test scores for a sample of fifteen students from each section, for a total of 30 participants in the experimental group and 30 participants in the control group. To ensure equal distribution of general student performance level, we looked at students’ overall course grade and randomly chose five high-performing, five average and five low-performing students from each section. High-performing students achieved a final course grade of 80 percent or higher. Average performance was defined as 70 to 79 percent. A low performance was defined by achieving a score of 69 percent or lower. This was reasonable, as course grades followed a typical bell curve distribution.

Results

Question 1 asks students to complete the phrase "To reduce the amount of greenhouse gas in the atmosphere, we need to…" Students should have chosen the correct answer from five options. The complete question and answer set can be found in the appendix.

Table 3 shows the pre-test and post-test results for Question 1. The control group showed a larger increase in the percent of students who answered the question correctly. 43.3 percent of the control group students answered the question correctly on the pre-test and 53.3 percent of the students answered correctly on the post-test, for an increase of 10 percent. 40 percent of the experimental group's students answered the question correctly on the pre-test, while 46.7 percent answered correctly on the post-test, for an increase of 6.7 percent.

Table-3 Pre- and post-test results for Question 1

	% Correct Pre test	% Correct Post test	% Increase
Control Group	43.3	53.3	**10.0**
Experimental Group	40.0	46.7	**6.7**

Table 4 shows the pre-test and post-test results for Question 2: If birth rate is falling in stage 3, why is total population increasing in stage 3? Both groups demonstrated an increase in the number of students who answered Question 2 using upper level systems thinking skills. The control group showed a greater increase than the experimental group, increasing from a pre-test percentage of 53.3 to a post-test percentage of 76.6. The experimental group increased from 66.6 percent, pre-test to 73.3 percent, post-test.

Table-4 Pre- and post-test results for Question 2

	Pre test **% Level 2 or 3**	Post test **% Level 2 or 3**	% Increase
Control Group	53.3	76.6	**23.3**
Experimental Group	66.6	73.3	**6.6**

The last three questions were only administered on the final exam. For these questions the experimental group is compared to the control group. Table 4 shows the control and experimental class results for the last three questions.

The first question was multiple choice and asked students to identify the correct inflow and outflow conditions for a stock to increase. The control group outperformed the experimental group, with 93.3 percent of the students answering correctly. 86.6 percent of the experimental group's students answered the question correctly.

The second question was multiple choice and asked students to identify the correct inflow and outflow conditions for a stock to decrease. The experimental group outperformed the control group, with 40.0 percent of the students answering correctly. 36.6 percent of the control group's students answered the question correctly.

The third question was short answer and asked student to explain what would have to be done to decrease carbon in the atmosphere. The experimental group outperformed the control group. 73.3 percent of the students in the experimental class delivered a Level 2 or Level 3 answer, compared to 66.6 percent in the control group.

Table-4 Pre- and post-test results for Question 2

	Stock increase (Multiple choice) % correct	Stock decrease (Multiple choice) % correct	CO_2 in atmosphere Decrease (Short answer) % Level 2 or 3
Control Group	**93.3**	**36.6**	**66.6**
Experimental Group	**86.6**	**40.0**	**73.3**

Discussion

The data has produced some results that we expected to see and some results counter to what we expected. As with preliminary studies conducted in the fall of 2008, the experimental group did not consistently outperform the control group. The hypothesis, in this case, was not supported.

Systems understanding increased noticeably for both groups, after instruction using to systems thinking skills. The control group was exposed to these skills textually, while the experimental group received some textual instruction, but also explored the concepts using a computer simulation. Both methods proved effective in increasing systems thinking ability.

Our hypothesis was not supported for two reasons: first, there were problems with the interventions conducted in class; second, there were problems with the assessment methods used to measure students' systemic understanding of environmental issues.

Intervention improvements

The Introduction to Environmental Science class was a semester long, or about four months. In that time, we used two assignments to introduce systems thinking concepts. We feel that more interventions would have been effective in increasing students' systems thinking abilities.

For some students the mechanics of operating the model seemed to distract from the lessons the simulation was intended to teach. Assignments used as interventions in the future should follow the same format to eliminate as much 'noise' as possible. The format would become clearer with each successive assignment.

Each assignment should be designed to look the same, relate the same concepts and have the same method of operation. This would be best accomplished by creating each assignment's reading material, simulation model and interface. For this study, we created the population activity, but used The Climate Bathtub Animation for the second assignment, as it was already available online. We designed questions to accompany the simulation activity that required students to think about the system structure underlying the simulation. Although the simulations had similar structures, they presented in very different ways, masking their similarities.

Assessment improvements

There were too few questions asked assessing students' systemic understanding. Future studies should include more pre-test/post-test questions. It would be easier to note any kind of trend in students understanding if more questions were used. It is hard to say conclusively, from just four questions, whether a student had a change in understanding. In many cases the same student answered some questions in a way the demonstrated a high level of understanding and some questions in a way that demonstrated little or no understanding. If more pre-test and post-test questions were asked, we could get a better sense of students' overall understanding.

If multiple choice questions are used, there need to be several of them. Again, this allows for trend recognition and eliminates skewing data when correct answers are chosen by chance.

Student performance on Question 3 and Question 4 tells us two things: first, when multiple choice questions are used in the assessments, all of the answer options should be delivered in the same format; second, students are less able to identify the correct answer when the answer option is numerical.

Question 3 asks students to identify the inflow/outflow conditions necessary for the stock to increase. Question 4 asks students to identify the inflow/outflow conditions necessary for the stock to decrease. The questions were worded identically and their answer options were the same. Figure 1 shows Question 3, Question 4 and the answer options given for both.

The results in Table 3 show that students performed very differently on these two questions. On Question 3, 93.3 of the control group's students and the 86.6 of the experimental group's students chose the correct answer. On Question 4, 36.6 of the control group's students and 40.0 percent of the experimental group's students chose the correct answer. The reason for the difference can be found in the way that the correct answer is expressed. The answer for Question 3 is c. RATE OF REMOVAL < RATE OF ADDITION. For Question 4, the answer is RATE OF ADDITION = 1,000,000 and RATE OF REMOVAL = 1,000,001. Both answers express the correct idea to answer the question, but students were less able to identify the correct answer that was numerical.

Figure 1-Questions 3 and 4 and answer options given for both

3. Under what conditions would the amount of the thing in the environment increase?

4. Under what conditions would the amount of the thing in the environment decrease?

a. RATE OF ADDITION = 1,000,000 and RATE OF REMOVAL = 1,000,001
b. RATE OF ADDITION = RATE OF REMOVAL
c. RATE OF REMOVAL < RATE OF ADDITION
d. RATE OF REMOVAL > RATE OF ADDITION
e. Cannot be determined with the information given.

In future studies, we would also include more 'generic structure' questions. Student answers showed a tendency toward explaining the behavior of a system not in terms of the structure they were given, but in terms of human behavior they are already familiar with. For example, in defining what would cause a decrease in carbon dioxide in the atmosphere, students were more likely to recommend a decrease in driving automobiles or a decrease in industrial activity than they would be to discuss the relationship between carbon emissions and carbon removal. One hypothesis as to why this occurred is that students may have already had a mental model of the systems used in the assignments. Using generic system structures, such as the ones described for Questions 3 and 4 would direct students to focus on the system's structure and not on what they may already know about the system.

Evaluating understanding

For this study, we evaluated student responses to short answer questions using the four levels of systems thinking previously explained, with the first level being no systemic understanding at all. As answers were evaluated, more subtle levels of understanding emerged than the four that we initially set out to evaluate.

1) Recognizing interconnections: Students could identify effect of changes in one part of system on another.
   - Example answer: Driving cars causes there to be more carbon in the atmosphere.
2) Understanding the effect of one flow independently on its related stock: describes the impact of changing either the inflow or the outflow on the stock in the system.
   - Example answer: An increase in carbon emissions causes an increase in carbon in the atmosphere.
3) Understanding the effect of both flows on their related stock: student relates both the inflow and the outflow to the stock in the system.
   - Example answer: We would have to increase carbon removal and decrease carbon emissions for carbon in the atmosphere to decrease.
4) Understanding how the stock accumulates in the system under equal inflow and outflow conditions: student could identify no change in the stock when given equal inflow and outflow and vice versa.
   - Example answer: The number of births would have to be equal to the number of deaths in order for population to stay the same.
5) Understanding how the stock accumulates in the system when inflow and outflow are not equal: student could identify an increase or decrease in the stock for a given set of inflow and outflow conditions and vice versa.
   - Example answer: The number of births would have to be greater than the number of deaths in order for total population to increase.

Students' systemic understanding seemed to progress through these five levels for questions about one-stock, two-flow systems. This information could be very useful in evaluating students' systemic understanding in future studies.

This study continues the work of determining the most effective way of increasing systemic understanding of environmental problems in that it tested the effect of systems interventions on a large audience. The preliminary findings show mixed results in the effectiveness of using computer simulations for such a large group, but the introduction of basic systems thinking skills produced a noticeable difference in systemic understanding of environmental problems for both the control and the experimental groups.

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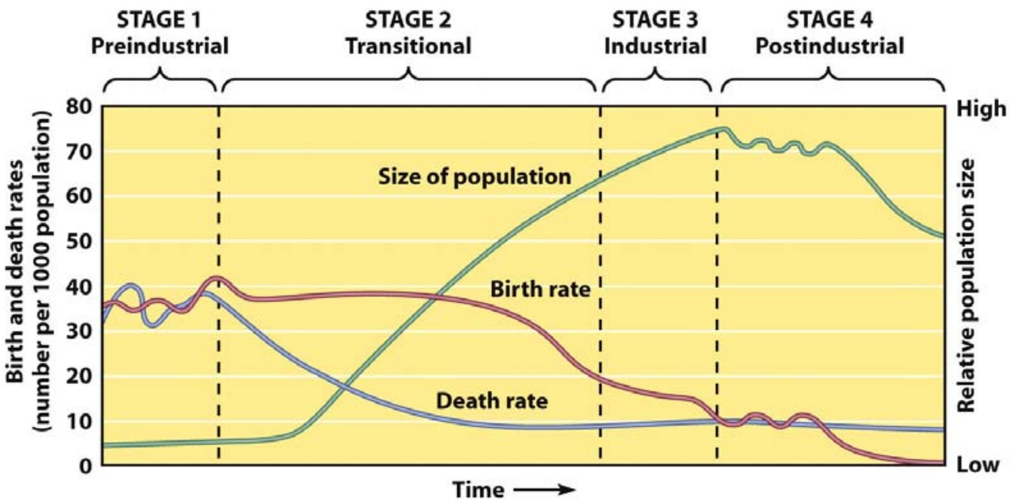
Appendix—Questions, correct responses, and systems thinking skills required to answer question correctly

1. The demographic transition graph below shows the relationship between birth rates, death rates and the overall size of the population at different stages of a society's economic development. Use the graph to answer the next three questions.



The birth rate is falling in STAGE 3. Why is the size of the population increasing in STAGE 3?

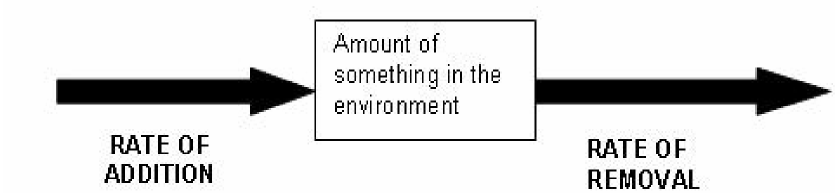
Even though birth rate is decreasing, it is still greater than death rate. As long as birth rate is greater than death rate, total population will increase, because more people are being added than taken away.

Systems thinking skills required:
-Recognizing interconnections.
-Understanding stocks and flows.
-Understanding accumulation in the system.

2. To reduce the amount of greenhouse gas in the atmosphere, we need to…
   a. Reduce the amount we add to the atmosphere each year by only 10 percent.
   b. Do nothing; the level of greenhouse gases in the atmosphere is decreasing naturally.
   c. Make sure the amount added to the atmosphere is less than the amount that is removed.
   d. It is not possible to reduce the amount of greenhouse gases in the atmosphere.
   e. None of the above

<u>Systems thinking skills required:</u>
-Recognizing interconnections.
-Understanding stocks and flows.
-Understanding accumulation in the system

For questions 3-5: Many environmental issues involve managing the accumulation of something in the environment. We generally want to increase the level of things we consider good, or valuable, and decrease the level of things we consider bad, or harmful. Some of the things we consider good are the amount of nutrients in the soil or level of dissolved oxygen in water. Some of the things we consider harmful include pesticides in the environment, or carbon dioxide in the atmosphere. We manage the levels of things in the environment by controlling the rate at which we add to the level or the rate at which we remove things, or some combination of the two. Use the diagram below to answer the next three questions.



3. Under what conditions would the amount of the thing in the environment increase?

   a. RATE OF ADDITION = 1,000,000 and RATE OF REMOVAL = 1,000,001
   b. RATE OF ADDITION = RATE OF REMOVAL
   c. RATE OF REMOVAL < RATE OF ADDITION
   d. RATE OF REMOVAL > RATE OF ADDITION
   e. Cannot be determined with the information given.

4. Under what conditions would the amount of the thing in the environment decrease?

   a. RATE OF ADDITION = 1,000,000 and RATE OF REMOVAL = 1,000,001
   b. RATE OF ADDITION = RATE OF REMOVAL
   c. RATE OF REMOVAL < RATE OF ADDITION
   d. RATE OF REMOVAL > RATE OF ADDITION
   e. Cannot be determined with the information given.

5. Based on this framework, what would have to be done to decrease the amount of carbon dioxide in the atmosphere?

Based on this framework, carbon emissions would have to be less than carbon removal for the amount of carbon in the atmosphere to decrease.

Systems thinking skills required:
-Recognizing interconnections.
-Understanding stocks and flows.
-Understanding accumulation in the system