Evaluating Students' Systems Thinking and System Dynamics Skills a systematic comparison at multiple educational levels.

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Introduction

In a world that is becoming more and more interrelated, complex and unpredictable and in which political, social, economic and ecological systems are in a continuous process of change systems thinking, system analysis and modelling offer a practical mean for gaining a better scientific understanding of system processes. Advocates of systems theory and systems thinking have postulated this claim frequently (e.g. Senge 1990[4]; Sterman 2000[5]). Existing studies reflected the usefulness of systems thinking interventions in many scientific and practical applications related to the fields of social sciences (Sterman 2000[6]) and environmental sciences. Stock and flow relationships are essential to the dynamics of systems and therefore need to be part of a systems thinking inventory (Forrester 1961[7]; Booth Sweeney and Sterman 2000[8]; Ossimitz 2002[9]).

In 2001, the School of Forest Science and Resource Management of the Technische Universität München, which offers traditional education in forest science, implemented the International Master of Science (MSc.) Programme in 'Sustainable Resource Management' (SRM). The aim of such courses is to provide graduates with an understanding of interrelated problems because forests are classic examples of complex systems involving long time spans, multi functionality and a variety of issues like climatology, recreation, ecology, economics, hydrology, law and politics. To understand and incorporate these factors into assessments, management plans and operational plans requires systems thinking skills or would be much improved if these skills were available. In order to educate students with skills related to sustainable development in land use and natural resource systems the curricula of both streams of education offer special courses that deal in particular with systems thinking, systems analysis and system dynamics (Biber and

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[4] SENGE Peter, (1990), *The Fifth Discipline: The Art and Practice of Learning Organisations*, Doubleday, New York.

[5] STERMAN John, (2000), *Business Dynamics: Systems Thinking for a Complex World*, Irwin McGraw-Hill, Boston.

[6] Ibid

[7] FORRESTER Jay, (1961), *Industrial Dynamics*, Cambridge, Massachusetts, Productivity Press.

[8] BOOTH SWEENEY Linda and STERMAN John, (2000), *Bathtub dynamics: initial results from a systems thinking inventory*, p. 249–286, System Dynamics Review Vol 16 System Dynamics Society, Albany (New York).

[9] OSSIMITZ Günther, (2002), *Stock-flow thinking and reading stock-flow-related graphs: an empirical investigation in dynamics thinking abilities*, Proceedings of the 2002 International System Dynamics Conference, System Dynamics Society, Albany (New York).

Kasperidus 2004[10]). Booth Sweeney and Sterman (2000)[11] introduced an inventory of tasks that assess systems thinking principles such as stock and flows, feedback, time delays and nonlinearities. Systematic research using this kind of tasks focus on students' ability to solve simple problems related to systems thinking. Students are asked to infer the behaviour of a stock from written and graphical information on the flows. In their first study Booth Sweeney and Sterman (2000)[12] revealed that students in the field of economics and business administration are not sufficiently prepared to take a full advantage of systems thinking and modelling. Since then, lecturers repeated the tasks at various levels of education and with different groups of students and pupils (e.g. Kapmeier and Zahn 2001[13], Ossimitz 2002[14], Booth Sweeney and Sterman 2002[15]) and confirmed that the test subjects have a poor understanding of basic concepts of systems thinking without special training.

With respect to the systems thinking education at the School of Forest Science and Resource Management we wanted to find out if the findings of the previous studies also apply to students in the environmental sciences? Are they better prepared in dealing with complex systemic issues that are common in land use and natural resource management? And more general, we wanted to find out how standard education programmes provide students with basic knowledge relevant to the field of systems thinking? Most interesting was to find out whether forestry students, especially the higher semesters, had developed the ability for systems thinking through their traditional education compared to the SRM students with special emphasis on systems analysis courses. The answer to these questions will help to get a better understanding of the students' initial ability to deal with the basic concepts of systems thinking. Moreover, it will help to align the contents of the courses and to provide the students with training that is tailored to their level of systems thinking ability.

Within a master thesis of the SRM programme we designed a study based on the systems thinking inventory and tested students from the school of forestry at different levels of education and in particular the first semester from the SRM programme to generate a comprehensive data set for analysis and comparison. An additional test group were the international students from the Postgraduate Specialization Course of the Masters Programme on 'Integrated Planning for Rural Development and Environmental Management' (IPRDEM) at the Mediterranean Agronomic Institute of Saragossa in Spain. We also included high school pupils in our study to find out if the education in mathematics (elementary calculus) is adequate to solve systems thinking problems. With these tests we have been able to increase the number of subjects' results of the systems thinking inventory that can be compared with other studies.

Method

We selected three tasks from the systems thinking inventory and adopted the assessment parameters and coding procedure to the requirement of the particular subject population. The

[10] BIBER Peter and KASPERIDUS Hans, (2004) *Integrated Modelling Approaches and System Dynamics in Education related to Sustainable Resource Management, Forestry, and Land Use Management*, Proceedings of the 2004 International System Dynamics Conference, System Dynamics Society, Albany (New York).

[11] Ibid

[12] Ibid

[13] KAPMEIER Florian and ZAHN Erich, (2001), *Bathtub Dynamics: results of a systems thinking inventory at the University of Stuttgart,* University Stuttgart (Stuttgart).

[14] OSSIMITZ Günther, (2002), *Stock-flow thinking and reading stock-flow-related graphs: an empirical investigation in dynamics thinking abilities*, Proceedings of the 2002 International System Dynamics Conference, System Dynamics Society, Albany (New York).

[15] Ibid

tasks involve simple algebra and straightforward logic as well the understanding and application of principles of systems, specifically stock and flow relationships, time delays and graphical integration. At university level the subjects filled out a standard background questionnaire on their demographics. The test language depended on the lecturing language of the courses; English, German, and Spanish. The subjects had 45 minutes to solve the three tasks, which is more time than was given in most of the previous studies. The following tasks were used in the test (for detailed descriptions of the tasks see Booth Sweeny and Sterman 2000)[16]:

Task 1: Department Store (DS)

This task is very simple and tests the students' ability to read graphs, to interpret the information on flows and to infer the effects of flows to stocks. It shows the graph of a rate of people leaving and entering a department store (the stock) during a 30 minute time period. The students are required to answer the following four questions and could gain one point per question:

Q1: During which minute did the most people enter the store?
Q2: During which minute did the most people leave the store?
Q3: During which minute were the most people in the store?
Q4: During which minute were the fewest people in the store?

Questions 1 and 2 relate to the flows and questions 3 and 4 to the accumulation of flows in the stock. The correct answer to the first two questions can be determined by detecting the peak of each flow on the graph. To answer question 3 the subjects need to identify when the number of people entering the store exceeds the number leaving the store, which is during minute 1 to 13. During this time the number of people in the department store increases and during minute 13 the most people are in the store. To answer question 4 the subjects need to identify when the number of people entering are lower then the number leaving which is during minute 14 to 30. The number of people is decreasing during this time period. To determine if the fewest people are at the beginning or at the end of the 30 minute period the subjects need to evaluate and compare the size of the area between the two flows during minute 1 to 13 and during minute 14 to 30. The area between the flows during minute 14 to 30 is greater meaning that more people left the store than entered during the previous period. The correct answer to question 4 is minute 30. Each correctly answered question received one point. According to the coding guide the correct answers had a variance of +/- 1. In addition a box with "Can not be determined" was available to be ticked.

Task 2: Bathtub (BT)

This task assesses the subjects' ability to track the changing quantity of water in a bathtub depending on its initial value and its inflow and outflow rates over the period of 16 minutes. The inflow follows a square wave pattern and the outflow is constant. The subject is required to draw changes in the stock as a trajectory on an empty graph. The task requires simple arithmetic in addition to an understanding of stock and flow relationships. Here the participants could score up to 7 points by successfully completing the following criteria:

1. When the inflow exceeds the outflow, the stock is rising. (no = 0, yes = 1)
2. When the outflow exceeds the inflow, the stock is falling. (no = 0, yes = 1)
3. The stock should not show any discontinuous jumps (it is piecewise continuous). (no = 0, yes = 1)
4. The peaks and troughs of the stock occur when the net flow crosses zero (i.e., t = 4, 8, 12). (no = 0, yes = 1)

[16] Ibid

5. During each segment the net flow is constant so the stock must be rising (or falling) linearly. (no = 0, yes = 1)
6. The slope of the stock during each segment is ±25 units/time period. (no = 0, yes = 1)
7. The stock peaks at 200 units and falls to a minimum of 100 units. (no = 0, yes = 1)

The task is very simple with no feedback processes and exogenous flows. Round numbers allow for easy calculation.

Task 3: Manufacturing Case (MC)

The MC task is a simple stock management situation covering a time period of 20 weeks. The setting is a manufacturing firm producing widgets at 10.000 units/week and with a 50.000 units inventory, which is to be maintained at all times. An unexpected increase in orders by 10 % occurs in week 5 and remains at this higher level requiring the production to be adjusted to the desired level. The changes in the production take four weeks to affect, which introduces a time delay to the stock and flow system with a single negative feedback loop. The subjects have to plot both, production and inventory, on separate time graphs. The task does not have a uniquely correct answer but a subject could score up to 7 points by covering the following criteria:

1. Production must start in equilibrium with orders. (no = 0, yes = 1)
2. Production must be constant prior to time 5 and indicate a lag of four weeks in the response to the step increase in orders. (no = 0, yes = 1)
3. Production must overshoot orders to replenish the inventory lost during the initial period when orders exceed production. Production should return to (or fluctuate around) the equilibrium rate of 11,000 widgets/week (to keep inventory at or fluctuating around the desired level). (no = 0, yes = 1)
4. Conservation of material: The area enclosed by production and orders during the overshoot of production (when production > orders) must equal the area enclosed by orders less production (when production < orders). (no = 0, yes = 1)
5. Inventory must initially decline (because production < orders). (no = 0, yes = 1)
6. Inventory must recover after dropping initially. (no = 0, yes = 1)
7. Inventory must be consistent with the trajectory of production and orders (no = 0, yes = 1).

Again, the task required no more than simple algebra to complete successfully.

Subjects

The four test groups received the same tasks and none of the participants were offered any incentive. The total number of participants was 154.

High school students at the Martin-Rinckart-Gymnasium, Eilenburg

This group (PUPIL) of 54 students, aged 15 – 17, consisted of three classes. By the time of the test the students had covered mathematical proof and linear, exponential and logarithmic functions. The mathematics teachers conducted the test with the students when they expected a regular exam according to their timetable. No mention was made of the background to the unfamiliar questions of tests and the pupils believed they were being graded. The students did not fill out the background questionnaire.

Students on the forestry course at the Technische Universität München

The students of the forestry course (FOR) were tested in two groups; one being mainly first semester students and the other was made up of higher semester students (5. – 7. semester). In this paper we handle them as one group of 43 students. The forestry students cover a range of topics during their 9-semester course. Among the topics covered are science and economics, natural scientific foundation of forestry, technical aspects of forestry production and economic and sociological foundations of forestry. The foundation course lasts 4 semesters and includes subjects such as mathematics, statistics, physics, general business management, general economics and theory of science. The extension courses of the higher semesters cover topics such as balance of matter in forest ecosystem, climatology, silviculture, forest yield science, engineering biology and business management in forest and timber industries, forest politics and management consultancy.

International Master of Science in Sustainable Resource Management (SRM)

This is a three semester international master programme open to students from all over the world. The course is taught in English and covers a wide range of topics related to resource management. The first semester includes basic courses such as environmental resource economics, information management, remote sensing and project management. During the second semester the students selected two elective courses as their focus. The third semester is spent on the master thesis. The first semester also includes an 8 hour lecture on systems thinking taught by Hans Kasperidus as well as a 33 hours course on system analysis which incorporates modelling exercises in a computer lab using STELLA software. There were 34 participants who took part in the test.

International Master of Science in Integrated Planning for Rural Development and Environmental Management

The students in the Postgraduate Specialization Course of the Masters Programme on Integrated Planning for Rural Development and Environmental Management (IPRDEM) at the Mediterranean Agronomic Institute of Saragossa, Spain are mainly from Mediterranean countries and South America. This programme is taught in Spanish and likewise includes a unit on qualitative modelling and system dynamics modelling with about 3 weeks with 6 hours per day on this subject. The test was handed out on the second day after the introduction into system theory. Of this course 23 students participated in the test.

Results

Graph 1 describes the four test groups compared to each other depending on their total performance. In all groups the top score of 18 points was reached by one or more subjects. The Saragossa and SRM groups both have students, who were unable to score one point. The forestry students outperform the other three test groups by showing a tendency of achieving better total scores as well as having a higher minimum score than the other groups. The SRM group shows the poorest total score followed closely by the IPRDEM students. These are also the groups with the lowest median score closely followed by the pupils. The forestry students produced results with a median value around 10 points. The other three groups have the majority of total scores below the 10 point mark.

Graph 1: Boxplot showing the total performance for the different test groups.

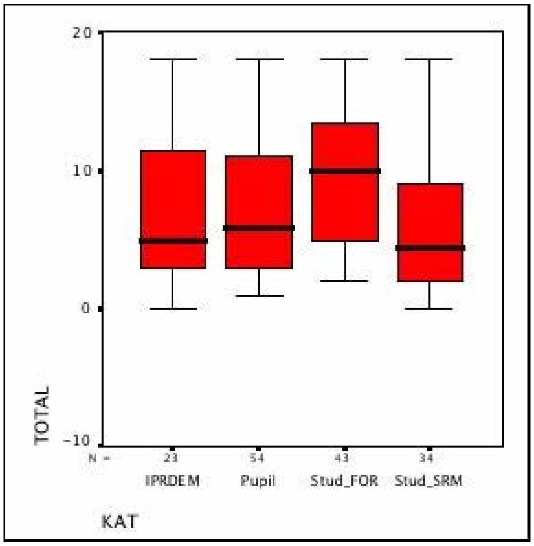

Table 1 shows the average performance expressed as the actual score divided by the maximum score of each group according to the separate tasks and in total. All groups together achieved 42 % of the possible total score. Task 1 (DS) produced the best results for all groups with an average result of 57 %. Task 2 (BT) scored 7 % less on average and Task 3 (MC) results in an average performance of only 29 %. Overall performance was poor.
The forestry students achieved the highest mean result with a total of 54 % correct solutions to the questions. Their scores for both Task 2 (BT) and task 3 were much better than the other two groups with 63 % and 42 % respectively. Task 3 (MC) especially produced very good performance compared with the pupils (26 %) and SRM students (16 %). Here the performance gap is most obvious between the groups. Task 2 also allowed the forestry students to jump ahead of the SRM students by 24 %. This task produced the best individual performance by any group with an average of 63 % correct answers. Task 1 (DS) produced very similar results for the individual groups.

Table 1: Average performance by task and in total. Performance is expressed as the actual score divided by the maximum score.

Group	N	Total	Task 1 (DS)	Task 2 (BT)	Task 3 (MC)
Pupils	54	0.41	0.57	0.47	0.26
SRM	34	0.34	0.58	0.39	0.16
IPRDEM	23	0.36	0.53	0.32	0.30
Forestry	43	0.54	0.57	0.63	0.42
Total	154	0.42	0.56	0.48	0.29

Typical mistakes occurred as demonstrated in other articles (Kapmeier 2001[17] and Booth Sweeney and Sterman 2000[18]). The common mistakes for task 1 are cases where subjects believed minute 8 to be the time when most people are in the store and minute 16 when the fewest people are in the store. Minute 8 is the time when the difference in the flows is at its' highest and when the least people are leaving. The subjects who answer the questions in this way show a lack of differentiation between accumulation and the net rate. For Task 2 (BT) the

[17] Ibid
[18] Ibid

common mistakes were spreadsheet thinking (instead of drawing continuous lines for the changes in water level, the change is shown as steps) and pattern matching (the subject transferred the inflow or outflow pattern directly to the changes in water quantity). Task 3 (MC) also included spreadsheet thinking and pattern matching (in this case transferring the order line directly to the inventory graph) as well as not showing a production overshoot, not letting the production and inventory starting in equilibrium with the orders and not matching the content of the production graph to the inventory graph.

Comparison with other studies

An important aspect of the selected standardized tasks is the comparability with similar studies conducted with other groups. The following paragraphs will show how the test groups from this study compare with the students tested by Booth Sweeney and Sterman at MIT in 2000[19] and Kapmeier and Zahn[20] with the students from the Stuttgart Institute of Management and Technology (SIMT) 2003 and the University of Stuttgart from 2000 – 2001 and 2002 – 2003. The MIT group consisted mainly of MBA students from the MIT Sloan School of Management. The second group were students on the System Dynamics course at the University of Stuttgart and in the third case the students were on the Business Modelling course on an MBA programme at SIMT. The comparison will be limited to the mean performance per task. Table 2 shows the difference in mean performance by task and group.

Table 2: Average performance by task and group in percent for the study at hand and other studies. Performance is expressed as the actual score divided by the maximum score.
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Group	Task 1 (DS)	Task 2 (BT)	Task 3 (MC)
Pupils	0.57	0.47	0.26
SRM	0.58	0.39	0.16
IPRDEM	0.53	0.32	0.30
Forestry	0.57	0.63	0.42
MIT (2000)	0.65	0.83	0.46
SIMT (2003)	0.66	0.65	0.31
University Stuttgart (2000 - 2001)	N/A	0.68	0.69
University Stuttgart (2002 - 2003)	0.67	0.83	0.62

The subjects from MIT and the University of Stuttgart show the overall best results whereas the SRM students performed poorly in comparison. Only the forestry students come close to competing with the SIMT group on Task 2 (BT) and Task 3 (MC) and with the MIT students on Task 3 (MC). The school students came close to competing with the SIMT group on Task 3 (MC). Nevertheless the studies used for the comparison come to the conclusion that the performance is poor (Booth Sweeny and Sterman 2000[21]; Kapmeier and Zahn 2001[22]).

[19] Ibid
[20] Ibid
[21] Ibid
[22] Ibid

Discussion

The research results show that the participants have a poor understanding of system principles, such as stocks and flows, time delays and feedback. However, in every group some subjects gained full marks for the whole tests even the group of pupils. That shows that it was possible to solve the test with the given information. A sizeable number of subjects produced fundamental errors in their handling of system tasks and not just calculation mistakes. Besides, the required calculations were straightforward and should not have caused serious problems for subjects with their level of education. In the case of Task 1 (DS) subjects were able to understand the graph but failed to accumulate flows. Task 2 (BT) caused many students to draw stock trajectories similar to the net rate, thereby failing to prove that they understand the difference between the net flow into a stock and how this reflects on the stock trajectory. Task 3 (MC) showed fundamental systems thinking errors as the subjects ignored the conservation of material and failed to match the inventory to the production lines. This is also the conclusion that other studies have reached notably Kapmeier and Zahn (2001)[23] and Booth Sweeney and Sterman (2000)[24]. The poor performance is despite the fact, that two of the current test groups were at university level, although the forestry group was composed of a large number of first semester students. The SRM students were even at master level and had received a lecture in systems thinking and system dynamics prior to the test. The three groups of the current study performed poorly individually, but particular differences lay between the forestry students and the SRM subjects. This was the case for the total results and in the case of Task 3 (MC). The difficulties, which this task caused for all three groups, possibly due to the appearance of a time delay and the necessity to conserve matter and match the production line to the inventory graph, were more easily dealt with by the forestry students whereas the SRM group produced their poorest results here. The school groups' performance rate lies between the other two groups but towards the lower end. How could these differences come about? Subject demographics for the SRM students showed no significant impact, although the main differences between these two groups are their origin (and therefore different school backgrounds) and their previous studies and degrees (again a different university education or no previous university degree). If the argumentation follows the line that the more education, the better the results should be, then the SRM should have produced the best results of all three groups. In reality theirs were the poorest.

The content of the forestry course provides sufficient input towards systems thinking abilities to produce better results than the SRM subjects. The performance differences show that the school students – although not significantly better – nevertheless produced better results again than the SRM group. We conclude that the curriculum and teaching in an average German high school (in this case located in the federal state of Saxony) covers enough ground to outperform the SRM group. Is education - current and previous - a key factor in promoting systems thinking skills? Booth Sweeney and Sterman (2000)[25] found that there was only a weak link between education and performance, but their test groups outperformed the groups of this study, in particular the SRM group. The students from MIT were able to produce 44 % better results on Task 2 (BT) task than the SRM group and still 30 % better at answering Task 3 (MC). This is a considerable advantage. Yet the difference for Task 1 (DS) was merely 7 %. In the case of the forestry students the gap was smaller (20 % better for Task 2 (BT) and only 4 % for Task 3 (MC)). Booth Sweeney and Sterman state that their test groups consisted of "highly educated subjects with extensive training in mathematics and science…" and "many had years of coursework and even

[23] Ibid
[24] Ibid
[25] Ibid

undergraduate or graduate degrees in mathematics, engineering or the sciences". A higher performance than a group of 16-year-old school students would be expected. And although this proved to be the case (8 % better for Task 1 (DS), 36 % for Task 2 (BT) and 20 % for Task 3 (MC)), do these results reflect the differences in education, training and experience? According to Booth Sweeney and Sterman (2000)[26] the MIT results are disappointing for a group of such highly qualified persons, which would place the pupils in a comparatively good position.
The other comparative groups (assessed by Kapmeier and Zahn 2001)[27] generally show a higher performance than the subjects from this study. An exception is Task 3 (MC) where the forestry students produced results 9 % better than the SIMT group. The University of Stuttgart group from both test years show a considerably higher performance for all three tasks than any of the groups from the current study. The success in Task 3 (MC) was related to the student's experiences with production issues during their university course, thereby supporting the idea that specific education will improve systems thinking skills. These groups were at master level with business administration and engineering as their main backgrounds and the authors state that a higher level of ambition has been observed in the students over the years, especially those that included system dynamics in their elective course. Yet despite this Kapmeier and Zahn (2001)[28] draw the same conclusion as Booth Sweeney and Sterman (2000)[29] that the results, with regards to the simplicity of the tasks, are far too poor. This study joins the conclusions of the other research mentioned here.

Conclusions

This paper wanted to assess whether students on environmental and natural resource management courses, with their implied focus on interconnection and complexity, are capable of working out systems thinking tasks. The results showed considerable lack of understanding of basic concepts of systems thinking and system dynamics as well as deficits in graphical integration and logical thought. Their performance is lower than the performance of the students in the other study groups. The same test should be carried out with additional groups to consolidate this claim. In any case, the design of the lectures in systems analysis and system dynamics has to consider these results, in particular in allowing enough time to teach these basic skills. It will be of great interest to compare the students' systems thinking skills after the training to see if there is any significant progress. A further way would be to apply system thinking and system dynamics as early as possible at high school level. Some points need to be incorporated into teaching and learning system dynamics in schools. Learner-centred learning is an essential method for learning system dynamics. With system dynamics the teacher is no longer the dispenser of information but a guide to the self-motivating and self-learning student. And learning becomes an active process of self-organised construction of meaning (Schecker 1994)[30]. Start simple and allow for enough time. System dynamics modelling should begin with basic structures using causal loop diagrams and verbal descriptions before moving on to stock and flow diagrams and equations. As the students start to grasp the concept and become more proficient at designing models the complexity can increase. Booth Sweeney and Sterman (2000)[31] consider a focus on the basics of systems to be important; stocks and flows, time delays and feedback processes and developing an

[26] Ibid
[27] Ibid
[28] Ibid
[29] Ibid
[30] SCHECKER Horst, (1994), *System Dynamics in High School Physics 1*, Proceedings — Education — of the 1994 International System Dynamics Conference, p. 74-84, System Dynamics Society, Albany (New York).
[31] Ibid

intuitive approach to systems. A key component of teaching and learning system dynamics is computer technology including the relevant software. Modern computer provide sufficient capacity for calculating complex models as well as providing the necessary desktop displays for interactive model building and testing. Nevertheless the basic structures and principles of system dynamics need to be mentally understood and model building and conception need to be simple at first before progressing to more complex models. The teacher is the key to success. Consistency and continuity as well as a broadening and deepening of the skills can be achieved. And the teacher is able to foster motivation and interest among the pupils as well as being the students principle learning guide. This requires highly motivated and interested teachers. “Students should come out of a systems education convinced that a much better understanding is possible in the present puzzling behaviour of personal, social, economic, and business situations” (Forrester 1994)[32]. As Edwards (1999)[33] fittingly writes “what lies ahead is the still-constant movement of engagement and retreat, two steps forward and one step back, that demands the courage and conviction to carry on regardless.” Hard work lies ahead in spreading the use of systems thinking and system dynamics in education, but it will be worthwhile and certainly needs to be done.

[32] FORRESTER Jay (1994), *Learning through System Dynamics as Preparation for the 21st Century*. Keynote Address for Systems Thinking and Dynamic Modelling Conference for K-12 Education June 27-29, Concord Academy, (MA)

[33] EDWARDS Michael (1999), *Future Positive International Co-operation in the 21st Century*. Earthscan, London.