T.C.

BAHCESEHIR UNIVERSITY

GRADUATE SCHOOL OF

THE DEPARTMENT OF EDUCATIONAL TECHNOLOGY

THE EFFECT OF SOLVING ENVIRONMENTAL PROBLEMS WITH SYSTEMS THINKING TOOLS ON EIGHTH-GRADE STUDENTS' LINEAR EQUATIONS ACHIEVEMENT AND SYSTEM THINKING COMPREHENSION

MASTER'S THESIS

ECE ÜNSAL

ISTANBUL 2024

T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL OF
THE DEPARTMENT OF EDUCATIONAL TECHNOLOGY

THE EFFECT OF SOLVING ENVIRONMENTAL PROBLEMS WITH SYSTEMS THINKING TOOLS ON EIGHTH-GRADE STUDENTS' LINEAR EQUATIONS ACHIEVEMENT AND SYSTEM THINKING COMPREHENSION

MASTER'S THESIS

ECE ÜNSAL

THESIS ADVISOR

GÜRSU AŞIK

ISTANBUL 2024

T.C.

BAHCESEHIR UNIVERSITY

GRADUATE SCHOOL

MASTER THESIS APPROVAL FORM

Program Name:	Educational Technology (EN,T)
Student's Name and Surname:	Ece ÜNSAL
Name of the Thesis:	The effect of solving environmental problems with systems thinking tools on eighth-grade students' linear equations achievement and system thinking comprehension
Thesis Defense Date:	06.06.2024

This thesis has been approved by the Graduate School which has fulfilled the necessary conditions as Master thesis.

Doç. Dr. Yücel Batu SALMAN

Institute Director

This thesis was read by us, quality and content as a Master's thesis has been seen and accepted as sufficient.

	Title/Name	**Institution**	**Signature**
Thesis Advisor's	Asst. Prof. Gürsu AŞIK	Bahçeşehir University	
2nd Member:	Asst. Prof. Defne YABAŞ	Bahçeşehir University	
3rd Member:	Prof. Dr. Hasret NUHOĞLU	Maltepe University	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name:

Signature:

ABSTRACT

THE EFFECT OF SOLVING ENVIRONMENTAL PROBLEMS WITH SYSTEMS THINKING TOOLS ON EIGHTH-GRADE STUDENTS' LINEAR EQUATIONS ACHIEVEMENT AND SYSTEM THINKING COMPREHENSION

Ünsal, Ece
Master's Program in Educational Technology
Supervisor: Gürsu AŞIK

June 2024, 75 pages

The objective of this study is to examine the impact of integrating systems thinking into mathematics lessons on the mathematical achievement, comprehension of systems thinking, and attitudes towards teaching mathematics with systems thinking of eighth grade students. The study group consisted of 44 eighth grade students enrolled in a foundation middle school in Istanbul. A two-group post-test design was employed in the study. During the course of the study, lesson plans were implemented with the experimental group using systems thinking approach tools, while the control group was given the same lesson plans without using these tools. The Scientific Achievement Test (SAT) was administered to the experimental and control group students as a post-test to measure their achievement in linear equations. The System Dynamics Comprehension Test was administered to the experimental group students to measure their level of comprehension of system dynamics tools. In addition, the System Dynamics Comprehension Test was employed to assess the attitudes of the experimental group students towards system dynamics in mathematics. The findings of the study indicated that there was a statistically significant difference between the experimental and control groups in terms of scientific achievement test scores. There was a moderate relationship between the scientific achievement test and the System Dynamics Comprehension

Test. Over half of the students indicated that the use of system dynamics tools enhanced their understanding of the subject matter in mathematics lessons.

Keywords : Linear Equations, Systems Thinking, System Dynamics, Mathematics Education

ÖZ

ÇEVRE PROBLEMLERİNİ SİSTEM DİNAMİKLERİ İLE ÇÖZMENİN SEKİZİNCİ SINIF ÖĞRENCİLERİNİN DOĞRUSAL DENKLEMLERİ ÇÖZME BAŞARISI VE SİSTEM DİNAMİKLERİNİ ANLAMALARINA ETKİSİ

Ünsal, Ece

Eğitim Teknolojileri Yüksek Lisans Tezi

Tez Danışmanı: GÜRSU AŞIK

Haziran 2024,75 sayfa

Bu çalışmanın amacı, sistem düşüncesi yaklaşımının matematik dersinde doğrusal denklemler konusunda kullanılmasının, 8.sınıf öğrencilerinin matematik başarılarına, sistem düşüncesi yaklaşımını kavramalarına ve sistem düşüncesi yaklaşımıyla matematik dersleri işlenmesine yönelik tutumlarına etkisini araştırmaktır. Çalışma grubu, İstanbul ilinde bir vakıf ortaokulunda öğrenim gören 44 sekizinci sınıf öğrencisinden oluşmaktadır. Araştırmada iki gruplu sontest deseni kullanılmıştır. Araştırmanın uygulanması sırasında deney grubuna sistem düşüncesi yaklaşımı araçları kullanılarak ders planları uygulanmış, kontrol grubuna ise bu araçlar kullanılmadan aynı ders planları uygulanmıştır. Bilimsel Başarı Testi (SAT), deney ve kontrol grubu öğrencilerine öğrencilerin doğrusal denklemler konusundaki başarılarını ölçmek için son test olarak uygulanmıştır. Deney grubu öğrencilerinin sistem dinamikleri araçlarını kavrama düzeylerini ölçmek için Sistem Dinamikleri Kavrama Testi uygulanmıştır. Ayrıca, Sistem Dinamikleri Kavrama Testi dahilinde deney grubu öğrencilerinin sistem dinamikleri ile matematik dersleri işlenmesine ilişkin tutumları ölçülmüştür. Çalışmanın sonucu, bilimsel başarı testi puanlarına bakıldığında, deney ve kontrol grubu arasında istatistiksel olarak anlamlı bir fark olduğunu göstermiştir. Bilimsel başarı testi ve Sistem Dinamikleri Kavrama Testi arasında orta düzeyde bir ilişki görülmüştür. Öğrencilerin yarısından fazlası, sistem dinamikleri araçları ile ders işlenmesinin matematik derslerinde konunun anlaşılmasına destek olduğunu belirtmiştir.

Anahtar Kelimeler : Doğrusal Denklemler, Sistem Düşüncesi, Sistem Dinamikleri, Matematik Eğitimi

To Günay Karakale

ACKNOWLEDGEMENTS

I would like to express my profound gratitude to Emre Göktepe, an industrial engineer from the Systems Thinking Association, for his invaluable guidance, advice, and encouragement throughout the research process. I would also like to extend my gratitude to Meltem Ceylan Alibeyoğlu, the R&D Coordinator at Darüşşafaka Educational Institutions. I am grateful to them for their unwavering encouragement, motivation, and suggestions.

Furthermore, I was able to complete this study with the continuous support of my family and friends, and I am indebted to them for their assistance.

TABLE OF CONTENT

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

BOTG	Behavior Over Time Graph
HOTS	Higher Order Thinking Skills
LOTS	Lower Order Thinking Skills
MoNE	Ministry of National Education
SAT	Scientific Achievement Test
SCDT	System Dynamics Comprehension Test
WEF	World Economic Forum

Chapter 1

Introduction

1.1 Statement of the Problem

Mathematics has been defined many times in the literature until today. For example, the definition of mathematics in the Turkish Language Association is given as “The common name for the sciences that examine the properties of quantities based on principles such as arithmetic, algebra, and geometry” (Turkish Language Association, 2023). However, when we consider how mathematics as a science influences societies and in what ways, the definition of mathematics is much broader than this sentence (Bishop, 1991).

Mathematics has always been one of the main tools individuals utilize to address difficulties in their daily lives (Krantz, 2010). It gives one the capacity to take a multifaceted approach to problems, cultivate an analytical mindset, and make predictions (Korkmaz, Dündar & Yaman, 2016). However, mathematics in school often appears as a disconnected, abstract entity from students' everyday problems, making it challenging for them to understand (Bishop, 1991). This is why it's essential to make mathematical concepts concrete from an early age, bring problems from daily life into the classroom, and present them in their context (Lopes, Grando, & D'Ambrosio, 2017). When looking at the mathematics curriculum in Turkey, it primarily focuses on improving students' procedural skills while not allocating enough time to the application of higher-order thinking skills (Altıner, 2021).

Since 2018, the mathematics curriculum has included "contextual problems" which are questions that are contextualized in real-world settings. Additionally, contextual problems make up the majority of the content of central high school entrance tests (Ministry of National Education (MoNE), 2023). When examining the curriculum as a whole, it is evident that the lesson material falls short of providing students with the necessary skills to address these complex issue types (Arı, 2022). Additionally, Turkey takes part in the PISA exam, which is given every three years as part of the Programme for International Student Assessment. This test is a significant international evaluation of students' proficiency in the natural sciences and mathematics and reading. The results tend to indicate the overall quality of a country's education system (Putri & Hiltrimartin, 2020). PISA is an assessment that focuses on the ability to reason mathematically to solve problems, to use mathematical concepts and operations to explain and predict events in real-life situations (Organization for Economic Co-operation and Development (OECD), 2019). When we examine the PISA 2018 reports for Turkey, the level of achievement in mathematics, although it has increased compared to each previous exam, remains below the Organization for Economic Co-operation and Development (OECD) average (MoNE, 2019). In the report, under the topic of mathematical literacy, Turkey is stuck at the second level of proficiency, which involves performing simple mathematical operations such as extracting information from a single source and using this information in a single representation. The PISA 2018 report indicates that Turkish students have weak skills in interpreting mathematical knowledge, relating it to everyday life, transferring it, and developing strategies, especially in the context of mathematics lessons (OECD, 2019). When examining Figure 1 of the 2022 Pisa results, it appears that Turkey's math average has approached the OECD average. However, it is important to note that the OECD average has decreased due to the inclusion of countries with low math averages among OECD countries (MoNE, 2023).

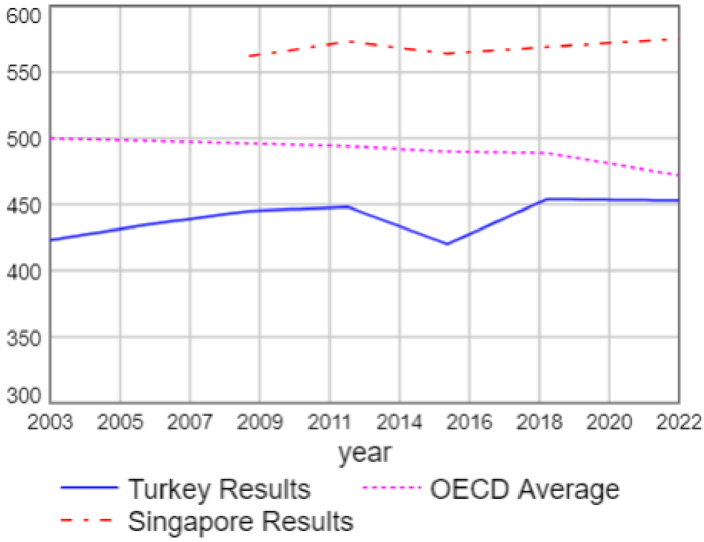

Figure 1. Averages for age 15 years PISA mathematics scale.

Indeed, a similar situation is observed in the standardized exam for the transition to high school. When we look at the results of these exams, which consist of contextual problems, we see that the lowest average is in the mathematics subject (MoNE, 2022). According to the PISA results and other research, students are better equipped for the 21st century by learning how to comprehend, analyze, transfer, and synthesize knowledge when mathematics lessons are integrated into everyday life within a context and incorporate elements of Bloom's Taxonomy (Bloom, 1956) (Hasibuan & Fauzi, 2019; Rosana, Widodo, Setianingsih & Setyawarno, 2020)

What does it mean to convey mathematical concepts within their context? The world is an intricate system made up of numerous interconnected systems (Şenaras & Sezen, 2017). A clearly stated problem is the first step towards building a framework that can produce solutions to complicated problems. Students must first comprehend these difficulties in order to apply the mathematical knowledge they learn in the curriculum to real-life situations (Squires et al., 2011). Examining the issue from all aspects is necessary when defining complex problems. It takes interdisciplinary thinking to approach problems from all angles. Real-world issues are, in fact, intrinsically multidisciplinary (Yanitsky, 2020). Students need to learn an interdisciplinary approach and the ability to look at things holistically to acquire these thinking practices (Lyneis, 1995).

The systems thinking approach encourages examining and evaluating the problems created by the complexity of a problem, paves the way for holistic thinking, and enhances the ability to reach better solutions (Maani & Maharaj, 2001). It develops students' thinking patterns in terms of how to address a problem, how to approach it, and which tools are appropriate (Ehrlinger & Eibach, 2011).

A problem may not have a simple linear cause-and-effect relationship. The solution to one problem can be the cause of another problem. On the other hand, a problem that seems to be solved in the short term may turn out to be a bigger problem in the long term. Systems thinking serves as a means to see all the cause-and-effect relationships in problems and to look at the whole picture rather than individual pieces (Ackoff, Addison & Carey, 2010). System dynamics tools facilitate the practical application of systems thinking in education, employing computer simulation to evaluate and refine mental models (Fisher & Systems Thinking Association, 2023). These tools are adaptable to different branches, suitable for all age levels, and useful. Students can better delineate real-life problems they encounter by designing numerical models using system dynamics tools within a simulation program. They can observe the movements of dynamic problems with behavioral graphs over time. In this way, they have the opportunity to find more sustainable solutions to problems (Göktepe, 2022). Furthermore to all of this, it is known that technological applications integrated into lessons in a way that contributes to learning increase students' motivation (Ginzburg & Barak, 2023; Poçan, Altay & Yaşaroğlu, 2023; Watson-Huggins & Trotman, 2019). The use of a simple simulation program (like the STELLA Online) that will help students see these relations and describe these relations numerically will also motivate students in this sense.

Simulation environments are created using system dynamics tools. In simulation environments, students experience a simulation of the real world with models. Multiple alternative experiments can be created in this simulation environment, and multiple experiments can be conducted. Students can generate solutions by experimenting with various scenarios they would not have the opportunity to try under different conditions in this simulation (Richmond & Peterson, 2001).

According to Assaraf and Orion (2010), in order to foster holistic thinking in students, systems thinking should be presented to them at a young age. Students will be more equipped to understand the intricate relationships behind the dynamic, social, economic, and environmental challenges they face and will be more driven to address them if they can make systems thinking a personal ability (Maani & Maharaj, 2004).

The Turkish education system should also be supported with approaches to self-directed learning and holistic thinking (Bulut, 2022). In Turkey, the Ministry of National Education (2006) aims to address this issue by incorporating constructive learning methods in new curriculum designs, but the educational programs and practices have not yet reached an adequate level (Arslan, 2007). The system dynamics approach, based on the philosophy of constructive learning, supports this framework as an interdisciplinary learning approach. Extending the examples and incorporating the systems dynamics method into the mathematics and other disciplines' curricula will help students investigate, define, and come up with comprehensive answers to the issues in their environment (Nuhoğlu, 2008).

The functioning of mathematical competencies in the current situation is modeled by the researcher in Figure 2. The mathematics curriculum in Figure 2 is centered on the Bloom Taxonomy's (Bloom, 1956) lower-order thinking skills (LOTS) (Figure 1) (Bloom, 1956). In Figure 2, the stock represents LOTS of a student. In other words, it refers to the fundamental concepts of a subject. We can consider processing skills within the context of mathematics lessons. The inflow of this stock is an increase in LOTS. One of the factors that increases the inflow is the teaching of lessons based on LOTS. In order to bridge the gap between the targeted success regarding LOTS and the existing achievement, it is necessary to process lessons focused on these skills. If these lessons are conducted, an increase in these skills will be observed, resulting in an inflow to the stock.

In contrast, Figure 3, which was modeled by the researcher, demonstrates that higher-order thinking skills (HOTS) are deliberately developed in addition to lower-order thinking skills (LOTS) in order to cultivate individuals with 21st-century skills. These skills are defined as the ability to analyze, synthesize, and transfer knowledge (Figure 2) as well as the capacity for autonomous learning (Bloom, 1956).

LOTS and HOTS appear as two skills that complement each other in Figure 3.. Similar to Figure 2, in Figure 3, the gap between the targeted success in terms of HOTS of a student and the existing achievement can be closed by processing lessons that enhance HOTS. Additionally, when the stock of LOTS reaches a level of readiness to acquire high-level thinking skills, it will also increase the inflow of HOTS. In Figure 3, HOTS form a stock. When this stock improves with transfer skills, it will also increase LOTS.

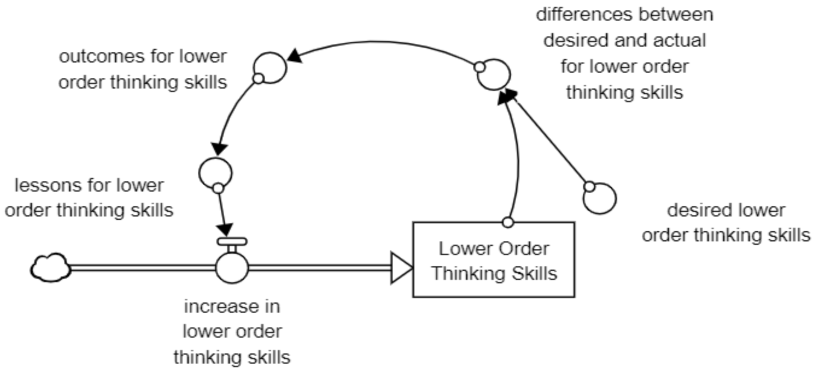

Figure 2. Mathematics competencies current situation.

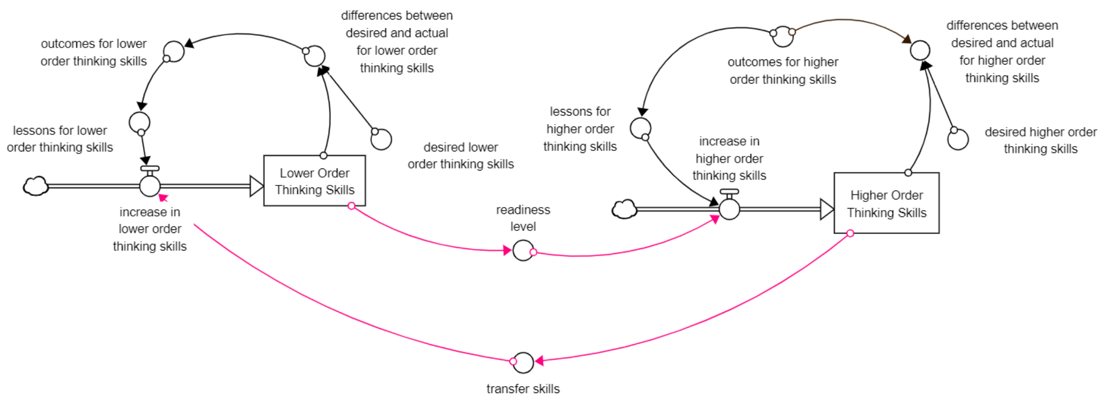

Figure 3. Mathematics competencies desired situation.

Lesson plans that support 21st-century skills lead to an increase in students' higher order thinking skill levels (Zainil, Kenedi, Indrawati & Handrianto, 2023). The increase in HOTS, in turn, nurtures LOTS. The current mathematics curriculum exhibits a discrepancy between the transfer of lower-level skills to higher-level skills and the mutual reinforcement of these two skills (Arı, 2022). This thesis contends that the gap between desired and current higher order skills will be reduced by incorporating and implementing the systems thinking approach into lessons, one of the educational approaches that will contribute to the development of the described skill.

Among the concepts that are challenging for students to grasp are algebra and, in conjunction with algebra, the system of linear equations. The transition from the concrete to the abstract can be confusing for students. Pulungan (2019) posits that when solving problems in the form of a system of linear equations, students encounter difficulties in comprehending the problems and in responding to the problems, particularly in mathematical modeling or strategizing. This may be attributed to students' inadequate conceptual comprehension of linear equations (Widada, et al., 2020). This thesis posits that system dynamics tools can facilitate conceptual understanding of linear equations.

1.2 Purpose of the Study

The aim of this study is to explore the effect of using system dynamics tools on understanding and comprehension of linear equations among 8th-grade middle school students. When we look at examples in the literature, we can see that the systems thinking in education contributes to the skills of the 21st century that are evolving in the light of technological advancements, and when integrated into lessons in a way that enhances learning, it increases student achievement in various skill areas (Richmond, 2010; Thornton, Peltier & Perreault, 2004). In light of these studies, the purpose of the study has been shaped as follows:

1. Enhancing students' skills in drawing linear graphs using numerical data in the digital simulation environment of STELLA Online, interpreting real-life situations as linear or non-linear through graphs, predicting the behavior of events over time, and drawing conclusions,
2. The objective is to facilitate students' capacity to interpret and comprehend causal relationships between variables through the use of models (Kim, 1999).
3. Increasing students' success in solving contextual problems related to linear equations,
4. It will enabling students to understand the systems thinking approach; To enable stock-flow and factors, which are basic tools of system dynamics, to establish their relationships with behavior graphs over time,
5. Lesson plans to be implemented with the systems thinking approach are inherently interdisciplinary (Yanitsky, 2020). Increasing students' motivation in mathematics classes through interdisciplinary lesson plans centered around real-life environmental problems adapted from real life,
6. Raising awareness and a sense of responsibility toward their environment among students through the integration of real environmental issues into the applications,
7. Observing potential issues during the implementation of the study and collecting data to minimize these issues in future similar applications,
8. The aim is to present examples of mathematics lesson plans created using the system dynamics approach in a way that serves as a model for mathematics

teachers and teacher candidates, with the goal of promoting the wider use of the system dynamics approach in education.

1.3 Research Questions

The purpose of this study is to investigate the impact of the system dynamics approach on students' achievement and system thinking comprehension in the learning of linear equations within the algebra unit in 8th-grade mathematics classes. The research questions that will form the basis of this study are as follows:

1. Is there a significant difference in the mathematical achievement scores related to linear equations, which are part of the algebra unit, between the experimental group and the control group students after the experimental process?
2. Is there a correlation between the scientific achievement test results of the experimental group students and their system dynamics comprehension test results?
3. How does teaching mathematics using the System Dynamics approach affect eighth-grade students' attitudes towards linear equations?

1.4 Significance of the Study

This study serves as an example of the use of systems thinking in education. The purpose of this research is to investigate how system dynamics-based lesson plans affect eighth-grade math students' understanding of systemic thinking and their achievement to solve linear equations throughout the algebra unit.

It was advised to use lesson plans created with a constructive approach that enhances higher-order learning skills, such as analyzing acquired knowledge, applying it to daily life, and interdisciplinary collaboration, in the Ministry of National Education's 2006 report (Aydın & Yılmaz, 2010). Despite the fact that this strategy has been used in many different ways since then, the 2018 PISA report shows that Turkish students have not improved in abilities including finishing simple mathematical operations and utilizing data from a single source (MoNE, 2019). The significance of the study lies in the proposal of a method, as system dynamics, which supports constructive teaching, can potentially bridge the gap between the current mathematics curriculum and a curriculum with lesson plans and outcomes that include higher order thinking skills.

There are many examples of the use of systems dynamics in education in Turkey and other countries (Fisher & Systems Thinking Association, 2023). Numerous research has been conducted, particularly in the scientific fields (Atmaca, 2019; Blatti et al., 2019). One of the factors contributing to the perceived difficulty of learning mathematics, compared to other subjects, including the natural sciences, is its more abstract nature (Reusser, 2000). Therefore, the importance of interdisciplinary studies in mathematics classes has increased (Sarsengeldin, Satabaldiyev, Meirambek & Guvercin, 2013). Additionally, one of the tools that enhances students' interest and motivation in the subject is the appropriate use of technology (Raja & Nagasubramani, 2018). This study consists of lesson plans based on creating numerical models using the simulation program in a digital environment, starting from real-life problems like environmental issues. Therefore, this study is also significant in highlighting the engaging and student-centered aspects of mathematics and algebra.

In the light of this study, it can be seen that activities created using system dynamics can be integrated into mathematics classrooms, and the findings of this study provide information for teachers, teacher candidates and researchers.

1.5 Definitions of Important Terms

Systems Thinking : Systems thinking is a comprehensive method that emphasizes understanding the relationships between the various aspects of a system, looking at external influences on the system, and viewing the system as a whole rather than just its component pieces (Richmond & Peterson, 2001).

System Dynamics : System dynamics complements systems thinking by quantifying the interrelationships in a system and developing an image of the time-dependent behavior of the system. Computer-based and simulation models are used to illustrate the complex relationships between variables (System Dynamics Society, n.d.).

Systems Thinking in Education : System dynamics tools can be used for Systems Thinking applications. It is recommended to start using the basic tools of system dynamics from preschool to create numerical models in the following years. This transition from the conceptual dimension to the numerical dimension helps to bridge the gap between system thinking and system dynamics (Systems Thinking Association, 2016).

STELLA (System Thinking Educational Learning Laboratory with Animation) Online: Stella Online is a simulation development program that consists of stock, flows, converter, and connector elements and enables you to see the interaction of variables in the system (Richmond, & Peterson, 2001).

System Dynamics Basic Tools:

Stock and Flow Diagram : "A visual depiction of the stock, flow and auxiliary (converter) variables in a system and how they are connected." (Ford, 2019, p.9). The basic stock flow diagram is shown in Figure 4.

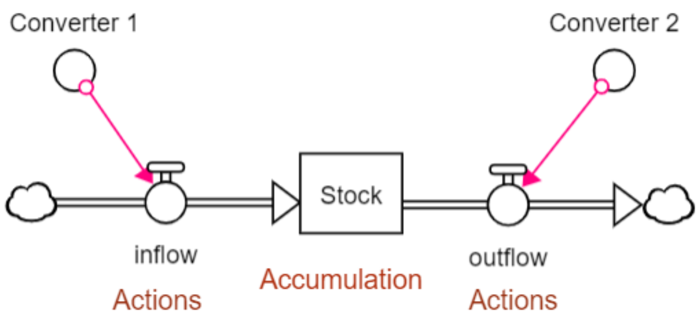

Figure 4. Stock - flow diagram.

- *Stock :* Stock is anything that can increase, decrease, change or accumulate (Fisher & Göktepe, 2021).
- *Flow :* Flow refers to actions that cause an increase or decrease in stock and accumulations, expressing changes (Fisher, 2018).
- *Converter :* includes connections or data that impact flow rates or the composition of another converter (Fisher, 2018).
- *Feedback Loop :* A feedback loop occurs when the inflows or output flows of a stock are affected by changes in that stock. A feedback loop is the flow

of causal links from a stock as a result of stock-dependent decisions, rules, or physical laws, which in turn affect the stock through the flow (Meadows, 2008).

- *Behavior (Change) Over Time Graph (BOTG)* : Line graphs are a useful tool for visualizing the behavior of a model over time. They show how one or more elements of a system change over time, with the horizontal axis representing time and the vertical axis representing a measurable, quantifiable, or abstract concept (Kim, 1999). An example of Behavior (Change) Over Time Graph is shown in Figure 5.

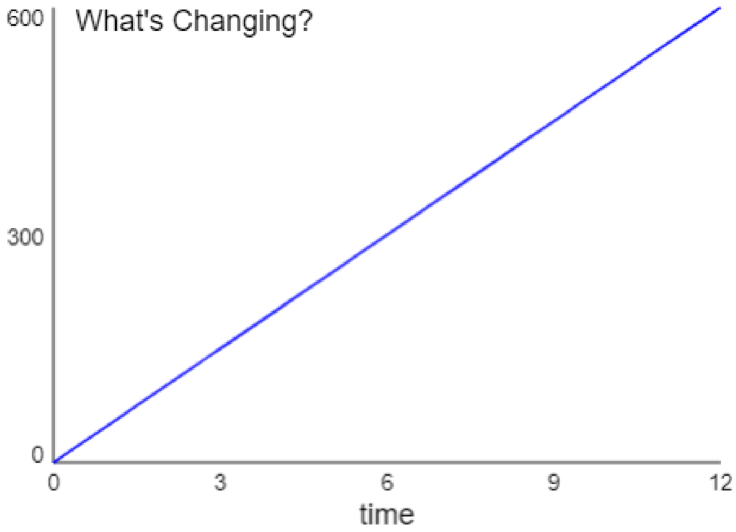

Figure 5. Behavior (Change) over time graph (BOTG).

Scientific Achievement Test : Eighth grade students' achievement scores obtained from the linear equations achievement test (SAT) consisting of 4 items prepared by the researcher based on the eighth grade linear equations learning objectives of MoNE (2018).

Systems Dynamics Comprehension Test : The post-test on system dynamics tools was administered to the students in the experimental group.

Chapter 2

Literature Review

This section presents a review of studies that are directly or closely related to the effects of using system dynamics tools in mathematics lessons on students' mathematics achievement, on students' understanding of system dynamics tools, and on students' attitudes towards mathematics. The review is presented in five sections: systems thinking, systems thinking in education, systems thinking and environmental problems, systems thinking and mathematics education, and finally, previous studies on the systems thinking approach.

2.1 Systems Thinking

A system is a complex structure formed by interdependent components with a specific purpose. The critical word is "relationship," and there must be a relationship among all the components (Barlas, 2007). When there is no interdependent relationship among the components, even if they come together, they cannot create a system; they only form a collection of parts (Kim, 1999).

Systems have a purpose, and this purpose manifests as the system's own goal; the purpose of the system cannot be defined by the individual goals of its parts. Systems strive to sustain themselves through feedback. Feedback is the transmission of information and its subsequent return to the system. For instance, after a person runs or climbs stairs quickly, their heart rate increases. If we think of the human body as a system, the system uses feedback to bring the heart rate back to its normal level (Kim, 1999).

Understanding systems and becoming a systems thinker involves grasping the purpose of systems and the relationships between their components (Anderson & Johnson, 1997). There are numerous descriptions of systems thinking in the literature. As we review Richmond's evolving conceptions of systems thinking, he has stated that systems thinking is the art of uncovering the understanding beneath something and deepening that understanding to make predictions about behavior

(Richmond, 1994). In later years, Richmond added the analogy of "thinking from 10,000 meters high, focusing on the forest rather than local trees" to his definition (Frank, Shaked & Kordova, 2016). According to Frank (2010), systems thinking is a highly developed cognitive ability that enables individuals to carry out system-related tasks successfully. He claims that systems thinking enables one to see the big picture or the overall issue rather than just the specifics of the system. In a similar vein, systems thinking, according to O'Connor and McDermott (1997), is about detecting deeper patterns than what may initially appear to be isolated and independent events. According to Senge (1990), systems thinking is a discipline for perceiving the big picture and provides a framework for seeing links rather than individual objects and dynamic patterns rather than static images.

Although there isn't a universally accepted single definition of systems thinking, the mentioned definitions all point to several common elements. Systems thinking is a holistic approach that focuses on seeing the whole rather than just the parts, explaining the relationships between the components that make up a system, and considering external factors that influence the system (Richmond & Peterson, 2001).

System Dynamics, which complements systems thinking and quantifies interactions between components, is a methodology that generates insights into the behavior of systems over time. It creates computer models to represent and simulate complex problems that change over time. These models allow us to see the forms of relationships between components, dynamic elements, and undesired outcomes (Fisher, 2005). As a result, the systems thinking approach shows promise as a powerful technique for comprehending complex issues at their root and providing answers (Elm & Goldenson, 2012).

The recent COVID-19 pandemic provides an illustrative example of a complex problem. In order to identify the root cause of this problem and develop sustainable solutions to the pandemic, systems engineers created a business response model based on systems thinking during the pandemic. The model, when provided with sufficient data, is capable of comprehending the complexities of the COVID-19 crisis and can be utilized in the future by incorporating additional variables when confronted with such challenges (Zięba, 2022). A systems thinking approach is essential for comprehending dynamic problems such as the ongoing pandemic, as Senge (1990) posits.

2.2 Systems Thinking in Education

With the rapid development of science and technology, new competencies and skills that can keep pace with these advancements are emerging. What we refer to as 21st-century skills, such as creative and computational thinking, modeling, graphic reading, information transfer, and technology utilization, are continually evolving. At the same time, technological progress is giving rise to new systems and leading to the formation of interconnected, much more complex systems. Changes made in one country have a much greater impact on other countries. Therefore, the importance of understanding the systems we are in is steadily increasing (Arnold & Wade, 2015).

The report released by the World Economic Forum (WEF) (2023) is based on research seeking to identify expected changes in jobs, competencies, and strategies between 2023 and 2027. Among the 26 competencies listed in this report, one of them is systems thinking and holistic thinking. The report emphasizes that the importance of systems thinking, especially among companies in the electronic, education, and training industries, is increasing, and it is considered a fundamental skill for employees. Additionally, the report highlights that systems thinking contributes to the teaching of skills in areas such as analytical and creative thinking, literacy (WEF, 2023)

The underlying holistic approach at the core of systems thinking inherently calls for an interdisciplinary perspective, and an interdisciplinary approach fosters holistic thinking (Sterman, 2002). When we look at the prevailing understanding in the education system in Turkey, many topics and units are compartmentalized into distinct sections. This approach aims to deliver information within these compartments most effectively. Therefore, students tend to view the world as if it were made up of multiple knowledge boxes (Nagarajan & Overton, 2019). One of the most important questions is: "Does imparting this information to students prepare them for the competencies of the 21st century?"A review of the mental models employed in the knowledge acquisition process reveals that these models consist of discrete pieces of information that are not related to each other. In the process of acquiring knowledge, students do not consider how these pieces of information interact with each other or the elements that may be involved in this interaction. This is because the education system leaves it to students to find or establish the relationships that exist between these isolated pieces. Furthermore, students are unable to perceive interdisciplinary interactions, or to think in a holistic manner. This thinking pattern is more reliant on cause-and-effect relationships and follows a one-way, linear approach. It's like X affects Y, Y affects Z, and Z affects V, and so on. The problem with this approach is that it provides a very limited framework for understanding why and how events occur (Kim, 1999). However, the world is too complex to be linear. Understanding problems within the complexity of the real world and generating sustainable solutions to these problems can only be achieved by seeing the problem from all aspects (Squires et al., 2011). Systems thinking provides students with the skills to consider all aspects of something/behavior/event and helps us better understand the behavior of the system (Senge, 2006). This thinking style is based on the "feedback loop" approach. It acknowledges that events are connected through interrelated and feedback loops, such as X affecting Y, Y affecting Z, and Z affecting X (Kim, 1999).

The vehicle for the use of systems thinking in education is system dynamics. System dynamics is a powerful method and computer simulation modeling technique used to frame, analyze, and discuss complex issues and problems (Richardson, 1999). Forrester (1995) states that system dynamics will be fundamental for all disciplines from kindergarten to university. Research suggests that system dynamics offers an applicable worldview for various disciplines, including mathematics, physics, biology, environmental issues, social sciences, and many more (Forrester, 1995). To apply system dynamics, it's essential to have knowledge of the basic tools, which include stocks, flows, converters, stock-flow diagrams, and behavior over time graphs.

2.2.1 Systems thinking basic concepts. Stock; anything that can increase, decrease, or change can be called a stock. In a piggy bank system, the money accumulated in the piggy bank is a stock. Examples of stocks include population, water in a dam, knowledge level, temperature, and blood sugar level (Monat and Gannon, 2015).

Flow refers to actions that cause an increase or decrease in behavior, expressing changes. In the piggy bank system, flows are the actions of putting money into the piggy bank and taking money out of it. If we consider a person's reputation as a stock, then the person's good or bad behaviors are flows that change the stock (Forrester, 2009).

Births and deaths, incomes and expenditures, learning and forgetting, inflow of sugar into the bloodstream, and output of sugar from the bloodstream are examples of flows (Monat & Gannon, 2015). Stock flow diagram is represented as shown in Figure 6.

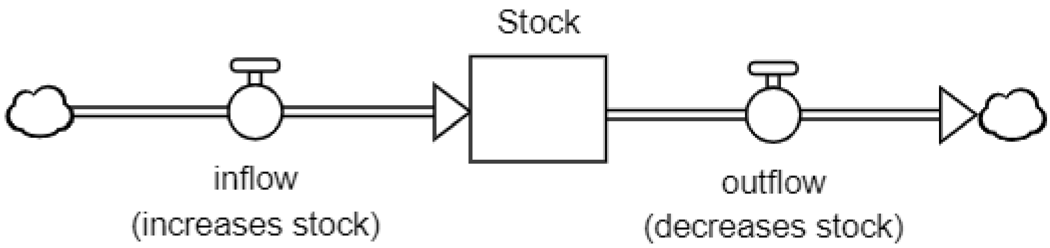

Figure 6. Stock-Flow diagram.

Causal factors are variables that influence flows. For example, in a model where the stock is the population, births are an inflow, and there is a birth rate that influences this flow. This is illustrated in Figure 7.

Flows can also be influenced by the stock they are connected to, creating a feedback loop. An example could be population dynamics. The Stock-Flow diagram for population is shown in Figure 7.

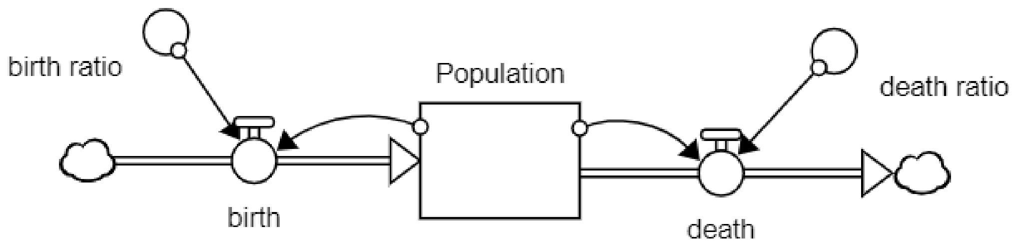

Figure 7. Population model.

The population has two flows: births and deaths. The birth flow increases the stock, while the death flow decreases it. Both flows are influenced by the population stock, and the stock determines what will happen to both flows. The population (and birth rate) determines how many births there will be, and the birth flow determines how much population there will be in the following period. The same holds true for the death flow. This interconnected relationship between stocks and flows creates a feedback loop that influences population dynamics (Nuhoğlu, Göktepe & Yararbaş, 2022).

Behavior Over Time Graph (BOTG) helps us visualize the behavior of a model over time. In this graph, the horizontal axis represents time. It allows us to see how the elements that make up the system change over time. Moreover, it shows us the relationships between the elements of the system. By adding numerical data to these relationships, we can make predictions and interpretations about the possible future behaviors of the elements (Nuhoğlu et al., 2022). The following diagram and graph (Figure 8.) illustrate the behavior of a model over time. The graph indicates that the water in the dams is increasing linearly. This suggests that the inflow into the stock is greater than the outflow from the stock.

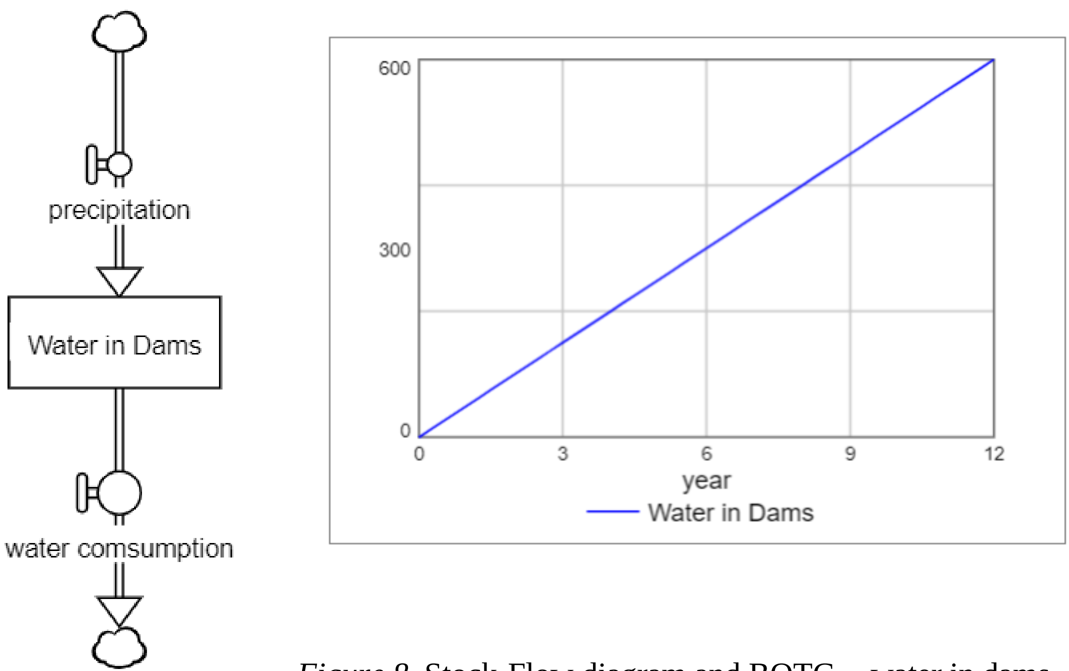

Figure 8. Stock-Flow diagram and BOTG - water in dams.

Using the basic tools of system dynamics, it is possible to create both very simple and highly complex models. Forrester (2009) shares the insights of a master's student after experiencing system dynamics:

In my differential equations class we used calculus to figure out the behavior of populations. I realized just how much simpler system dynamics made that thought process. Elementary scholars can understand the same things by using system dynamics modeling" (p.16).

It is anticipated that a relatively short amount of time would be sufficient for K-12 teachers to start using systems thinking tools in their lessons, and significant progress is expected in students' holistic thinking as a result (Forrester, 2009).

2.3 Systems Thinking in Education and Environmental Problems

Although the philosophy of systems thinking dates back to ancient times (Frodeman, Klein, & Pacheco, 2017), the use of system dynamics based on a systems thinking approach in many fields is relatively recent. System dynamics involves modeling time-varying stocks and flows. This modeling has increased, particularly since the publication of the report titled 'The Limits to Growth' by the Massachusetts Institute of Technology team commissioned by the Club of Rome in 1970 (Strapasson et al., 2022). The team analyzed the factors that determine and limit global growth in their report (Meadows, Meadows, Randers, & Behrens, 1972). A series of global development scenarios were constructed based on the aforementioned factors, with a particular focus on future scenarios pertaining to environmental events that may undergo change over time. To simulate the scenarios, they used the system dynamics simulation programmes recently established by Professor Jay Forrester (Turner, 2008). The report stated that the ongoing growth in global economies would lead to a collapse beyond the limits of the population and economic system in the 21st century. However, it also conveyed the message that this situation could be balanced with urgent policy and technological interventions (Meadows, Meadows, Randers, & Behrens, 1972). The publication of the report during this period made environmental issues and sustainability discussions even more important (Turner, 2008).

The use of system dynamics in education, including environmental education, can be traced back to the 1970s, when Professor Jay Forrester made significant contributions (Strapasson, 2022). Since then, system dynamics has been widely used in various fields such as mathematics, physics, social sciences, history, economics, biology, and literature, ranging from early childhood education to postgraduate level.

Environmental problems are generally dynamic and complex, requiring systemic solutions (Capra & Luisi, 2014). The structures within which environmental problems exist are not static, but constantly change over time, with variables intertwined (Doğança, 2013). Therefore, understanding the effects, structures, and future behaviors of these problems depends on recognizing the systems. In order for students to understand the fundamental purpose of environmental education and broaden their perspectives, a systemic approach is necessary (Doğança & Saysel, 2012). Systemic thinking is concerned with thinking about relationships and contexts and being able to see the world from a holistic perspective (Richmond & Peterson, 2001). For instance, instead of viewing climate change as solely an environmental issue, students should understand climate as a system and comprehend the connections between factors such as economics, politics, the natural sciences, and social life (as cited in Karaarslan Semiz & Teksöz, 2020).

Nevertheless, the education system is composed of fragmented disciplines (Brown, 1992). Environmental sustainability education, on the other hand, cannot be attained merely by acquiring knowledge about environmental issues (Assaraf & Orion, 2005). The fragmented nature and knowledge-centric focus of the education system further complicate students' understanding of the dynamics and complexity of the environment. The concept of systems thinking enables students to focus on the causes of events and understand that complex systems have many fundamental causal relationships that cannot be superficially resolved. Additionally, as a general problem definition and solving approach, it helps them develop skills such as discovering new problems by observing the environment, modeling and analyzing these problems using a scientific approach. Furthermore, the World Economic Forum (WEF) study from 2023 highlights how the systems thinking method helps teachers educate students abilities like literacy, analytical and creative thinking (WEF, 2023). For this purpose, there should be comprehensive tools that enable them to perceive environmental education in a holistic way, and these tools must incorporate a systems thinking approach. Tools for system dynamics satisfy these requirements. With tools like the Behavior Graph Over Time, Stock-Flow Diagram, and Causal Loop

Diagram, system dynamics is applicable to all educational levels and is simple to comprehend and implement. These tools enable numerical modeling in computer-based simulation programs. By using numerical data to model complex environmental problems, it is possible to predict their future behavior through a behavior graph over time (as cited in Fisher, 2018).

Sustainable Development Education (SDE) exhibits an approach based on systems thinking (Booth-Sweeney, 2017). It utilizes systems thinking to understand complex environmental issues, recognize future threats, effectively utilize natural resources, and address issues such as global warming and biodiversity loss (Wals, 2012).

In a study, it was found that teachers perceived ecological topics as simple for students, despite students having misconceptions about dynamic ecological problems in different classes (Grotzer & Basca, 2003). Additionally, there are limited educational materials that support students' development (Zaraza and Fisher, 1999). Therefore, system dynamics materials produced to understand and solve dynamic and complex problems should be increased at every level and in every field. Following this approach can students gain a complete understanding of environmental issues and develop practical solutions (Forrester, 1994).

Forrester (1992) argues that education presents a static image of dynamic real-world problems. System dynamics provides rich tools to transform education and, consequently, ecological problems from a static image to an integral part of real life.

2.4 Systems Thinking and Mathematics Education

Mathematics provides an approach that is used to systematically reveal structures or orders in any field (Uğurel & Moralı, 2008). Mathematical theories, on the other hand, are the product of relationships between mathematical concepts, and all relationships constitute mathematics, so it is necessary to understand that mathematics is a system (Michener, 1978).

Conceptual understanding refers to the close relationships between facts, laws and rules that form the basis of mathematical knowledge (Tashtoush et al., 2023). When students are able to see the relationships between mathematical concepts, show different representations of concepts and give examples of these concepts - that is, when they have conceptual understanding - they can carry out the procedures of using these concepts in a problem and solving the problem (Ferrini-Mundy, 2000; English, 2012).

A definition of problem solving from PISA (Programme for International Student Assessment) is as follows:

"… individuals' cognitive capacity to confront and solve interdisciplinary situations that do not fall within a single domain of applicable literacy or curricular areas of mathematics, science, or reading is known as problem-solving ability." (OECD, 2004, s. 26).

Shirawia and his colleagues (2023) define solving a mathematical problem as solving the abstracted state of the problem translated from the contextual level to the abstract level and translating the solution back to the original context of the problem. However, if we look at mathematics education, the applications are limited and students can create very limited mental models of concepts to solve problems. Therefore, they have difficulty in establishing relationships between other mathematical knowledge (Hubbard & West, 1997).

The systems thinking approach allows students to comprehend the problem before solving it and establish relationships between concepts by creating interactive models. Systems thinking is an approach that starts with a problem, represents the relationships of the factors affecting the problem, and moves towards the goal by continuously monitoring progress. It can be considered a unique form of problem-solving, similar to the problem-solving process (Adis et al., 2017). The integration of systems thinking activities into the curriculum from an early age, specifically in preschool and primary school, has been shown to enhance students' problem-solving abilities (Richmond, 2010). At the kindergarten and primary school levels, students are introduced to a range of system dynamics tools, from the relatively simple behavior graphs over time to the more complex stock-flow diagrams. The utilization of stock-flow diagrams by students to solve problems and develop this skill has been demonstrated to facilitate the acquisition of solutions to more complex numerical models in subsequent years (Opfer et al., 2018).

The following example (Yiğitgil, 2016) illustrates the use of stock-flow diagrams in primary school-level lessons for the purpose of teaching addition and subtraction. It is based on a problem written by a student.

> *Example Problem : I had 20 apples. I ate 8 of them. Then my mom bought 4 more apples. How many apples did I have?*

Prior to solving the problem, students must first identify the stock and determine the flows that affect it. They then proceed to the solution by entering the given numerical values into the stocks and flows (Demir, 2016). Figure 9 illustrates the stock-flow diagram created by the student to solve the problem. At this age, students typically create the diagram by manually drawing the stocks and flows on paper, without utilizing the Stella Online application. Once the model has been constructed, the student determines the final number of apples by performing the following calculations: 20 + 4 = 24 and 24 - 8 = 16.

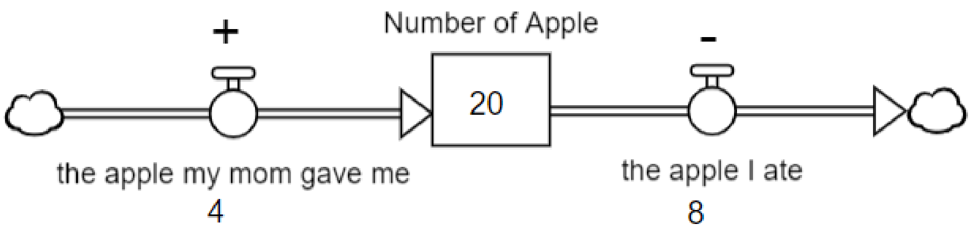

Figure 9. Elementary school level math problem stock - flow diagram (Yiğitgil, 2016).

The example presented above represents a solution to a problem written by a student. However, students may also work with pre existing problems. In addition to comprehending existing problems and developing solutions, the systems thinking approach also provides students with experience in generating and solving their own questions or scenarios at an early age. The work that begins with these examples can be transformed into graphs of appropriate mathematical equations and can be utilized to solve more complex problems (Göktepe, 2022).

Algebra is often challenging for students as it marks the transition from concrete to abstract thinking, using symbols instead of numbers. Additionally, it serves as the foundation for systems of linear equations, which can also pose difficulties for middle and high school students. Difficulties in understanding linear equations can stem from a lack of conceptual understanding, an inability to establish relationships between concepts, and an inability to use concepts in problem-solving. Additionally, creating graphs to represent linear equations and determining the intersection points of variables can also pose challenges (Tashtoush et al., 2023). A study on the system of linear equations in two variables supports these findings. The study revealed that students were able to perform mathematical operations but struggled with using mathematical modeling, elimination method, substitution method, and mixed methods to solve linear equations in two variables (Widada, 2020). When solving problems, students often make direct calculations that are detached from the real context of the problem (Salado, Chowdhury & Norton, 2019). These behaviors suggest that students may be applying rules without fully comprehending the underlying concepts, and simply memorizing information without a deeper understanding.

In her book, Fisher (2001) describes the system dynamics tools and experiences that can be applied in Algebra and Calculus subjects as a result of his studies with students. She mentions the relationship between algebra and system dynamics :

> "Systems dynamics provides what I believe a powerful framework for synthesizing the most important concepts that span Algebra, Pre-Calculus, and Calculus courses. By looking at functions from the standpoint of their behavior over time, one gains an understanding of the function itself, how it is different from other functions, and how it can be applied to understanding real-world phenomena. I think this is the primary purpose of the study of algebra.." (p.1).

Fisher provides examples (Figure 10) of how to explain algebraic lessons starting from the basics using system dynamics tools in her book. Furthermore, Fisher suggests that writing an equation for a physical situation, such as water flowing from a faucet, can be challenging for a student without these types of model representations (Fisher, 2001).

The following are examples of models created with the STELLA application for teaching algebra using system dynamics tools.

Example problem: "There is an empty barrel under a tap. Interpret the behavior of the water in the barrel when the tap is opened to a constant flow of 2 dm^3 per minute." (Fisher, 2001).

The text describes how a stock-flow diagram can be used to introduce algebra in a physical situation involving water in a barrel and a faucet. It emphasizes the importance of concretizing algebra by putting it in context.

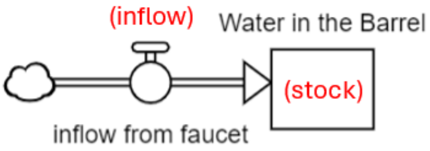

Figure 10. Stock-flow diagram of water in the barrel (Fisher, 2001).

The equation to determine the amount of water in the barrel after time t is : Initial Stock Value + 2t. Students can also create two graphs to illustrate the behavior of the water in the barrel over time. The graphs illustrate the change in water level in the barrel every minute, providing a clearer representation of the algebraic expression or equation written. Figure 11 illustrates two scenarios where the initial stock value is either zero or a value that differs from zero.

(Inıtial Stock Value = 0) (Initial Stock Value = 4)

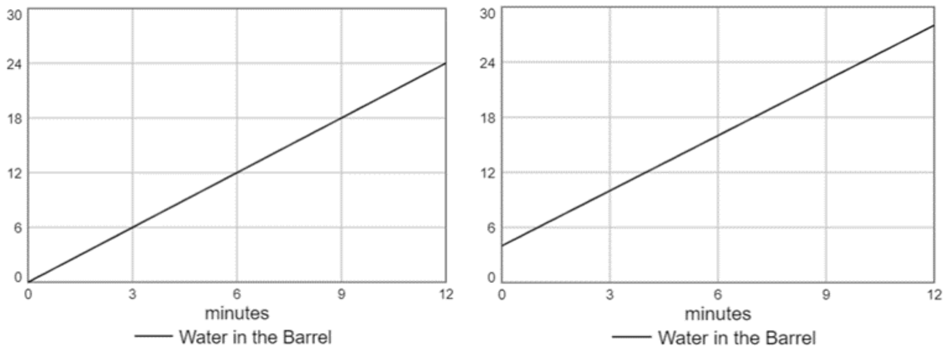

Figure 11. Behavior over time graphs (BOTG) of water in the barrel (Fisher, 2001).

Figure 12 presents a model with one factor affecting the outflow, unlike the model in Figure 11. The stock, which refers to the water in the barrel, decreases over time. The draining rate determines the level of reduction. Students can discuss the factors that contribute to the decrease of water in this model and determine the amount of water in the barrel at time t by writing an equation. The equation to determine the amount of water in the barrel after time t is : Initial Stock value - (draining rate x t). Figure 12 illustrates the linear decrease in water content in the stock over time due to desiccation. The outlet flow is influenced by a drying rate that affects drying.

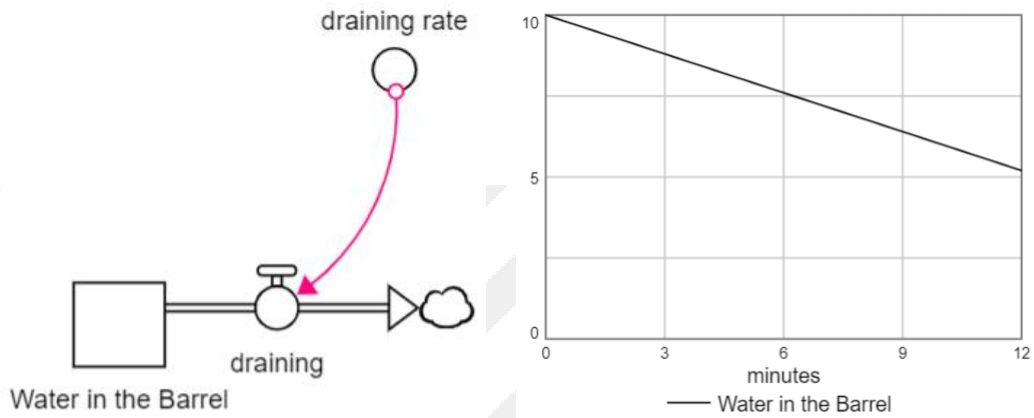

Figure 12. Water in the barrel 2 and B0TG of water in the barrel 2 (Fisher, 2001).

As problems become more complex, models progress from simple to complex. In the example model shown in Figure 13, there is a stock that directly affects the output flow, unlike the models above. Although novice algebra students may struggle to write the equation for this model, they can interpret it and discuss the factors that affect the situations. For experienced students, this model is ideal for discussing exponential expressions and nonlinear equations. Figure 13 illustrates a decreasingly decreasing model. This is due to the fact that the output flow is not constant but rather decreases in proportion to the value received from the stock per unit time.

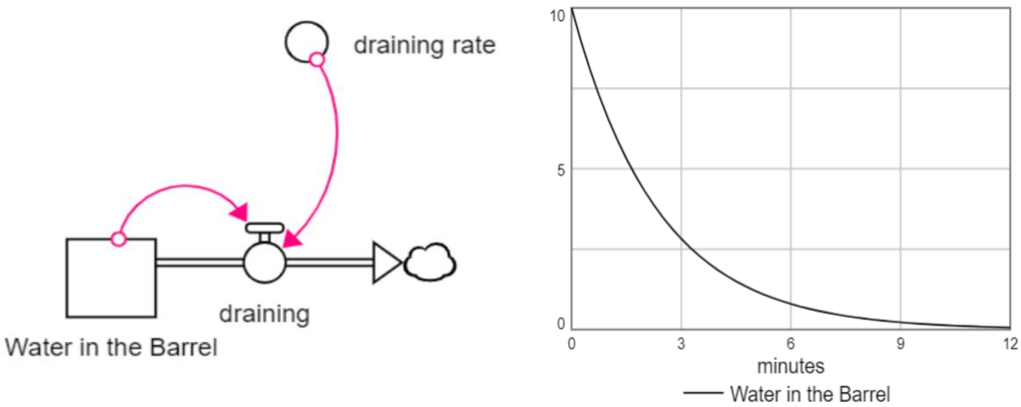

Figure 13. Water in the barrel 3 and B0TG of water in the barrel 3 (Fisher, 2001).

Moreover, system dynamics tools facilitate the transition from abstract to concrete concepts for students, as well as the creation of their own scenarios. This process involves the decomposition of complex problems into their constituent parts and the analysis of the relationships between models and graphs that illustrate changing behaviors over time. It also serves to reduce misconceptions. With these features, students are better able to comprehend the subject matter (Richmond, 2010).

2.5 Related Studies

Jay W. Forrester is considered to be the pioneer of the system dynamics approach that emerged in the United States during the 1950s. He created the system dynamics field, which involves computer modeling of systems thinking, to understand complex systems that change over time. Forrester developed computer-aided models using system dynamics (Forrester, 1968). System dynamics has been applied to various social systems, including the economy, environment, and health. In 1989, the Waters Foundation was established under the influence of Jay Forrester, which led to the application of system dynamics in the field of education (Waters Centre for Systems Thinking, n.d). Jay Forrester subsequently founded the 'Creative Learning Exchange' foundation to apply systems dynamics in K-12 education shortly after the establishment of the Waters Foundation (Creating Learning Exchange, 1991). Since their inception, both communities have worked to promote systems thinking and develop related skills among students and teachers. Thanks to these communities, interest in systems thinking studies has increased in various countries, particularly in the USA (Küçükoğlu, Nuhoğlu & Taşçı, 2023). STELLA (short for Systems Thinking, Experimental Learning Laboratory with Animation), the system dynamics software described in Richmond's book 'Introduction to Systems Thinking' (2004), has led to a greater application of system dynamics in education (Elmas et al., 2021).

In Turkey, the study of the systems thinking approach gained momentum in 1997 with the 15th System Dynamics Conference organized by Professor Dr Yaman Barlas. In 2008, Hasret Nuhoğlu published the first doctoral dissertation on systems thinking in Turkey. In this study, she employed system dynamics tools to assess students' achievement, attitudes, and diverse skills in elementary science and technology courses. Since the establishment of the Systems Thinking Association in 2016, studies on systems thinking in education have increased significantly, from primary school to university level (Sistem Düşüncesi Derneği, 2016).

The integration of the systems thinking approach into many disciplines and its application at all age levels has led to research into the impact of the approach on students. Feriver and Göktepe (2022) conducted a study with preschool students and observed that using the systems thinking approach to expand mental development in students around the age of five during the process of establishing cause-effect relationships yielded positive results. In a study conducted in a pre-school setting, the aim was to enhance students' environmental awareness through the use of system dynamics tools. It was observed that students with limited environmental awareness were able to define the environment more easily after receiving lessons that incorporated system dynamics tools (Kaya, Ellez & Ellez, 2019).

A study was conducted with second-grade primary school students in Turkish language lessons to investigate the effect of using a systems thinking approach on their reading comprehension skills. The results of the study showed that the use of system dynamics tools had a positive impact on the students' ability to extract deeper meaning from texts. Furthermore, in the tests administered after some time had passed, it was observed that the students provided similar answers, indicating that permanent learning had been achieved. In addition to facilitating in-depth learning of the subject, this approach also positively contributed to long-term retention of the material (Ulus, 2023).

Similar studies have been conducted at secondary, and high school levels. The study conducted by Doganca and Saysel (2018) found that 7th grade students who used system dynamics to study the food chain were more successful in understanding the concept and identifying feedback loops compared to the control group. Furthermore, the students did not face any difficulty in conducting similar studies even after some time had passed. Similar to the research findings above, the study suggests that the use of system dynamics can lead to permanent learning. In another study conducted by Riess and Mischo (2010), it was observed that the achievement scores of the 6th grade experimental group students working on the subject of forest ecosystem with system dynamics were significantly higher than those of the control group.

A study similar to the one carried out with the 2nd grade students in the Turkish language course was carried out with the high school students in the literature course on the topic of work analysis. The students in the experimental group who used system dynamics tools were able to look at the texts more broadly and holistically and to read more deeply (Çelikten, 2022). Fisher (2023) worked with high school students in a mathematics course and obtained positive results using system dynamics tools. These tools helped students recognise basic calculus concepts, create stock-flow with differential equations to obtain new equations, and gain a better understanding of the subject (Fisher & Systems Thinking Association, 2023).

The studies mentioned above have a common feature: system dynamics tools help students to achieve a deeper understanding of the subjects, to better comprehend the relationships between phenomena and have a positive impact on long-term learning. Concurrently, Aşık and Doğança (2021) posit that system dynamics facilitate the deployment of metacognitive abilities, including the identification of the task, analysis, and the formulation of a solution plan. It is important to identify the lessons where the systems thinking approach can be effectively applied, select appropriate tools for the students' level, and ensure that practitioners are competent in the systems thinking approach and system dynamics tools. Failure to do so may increase students' cognitive load and negatively impact their learning. The model in Tablo 1 displays the system dynamics tools available to students in different age ranges and their cognitive ability to identify relationships (Fisher & Systems

Thinking Association, 2023). This table can be incorporated into lesson plans involving system dynamics.

Table 1

Systems Thinking Concepts for K-12 Students (Fisher & Systems Thinking Association, 2023).

ST Concepts	Kindergarten	Primary School	Middle School	High School
Recognizing interconnections	One-to-one, many-to-one relations	many-to-one relations	one-to-many relations	many-to-many relations
Identifying feedback	no feedback	one loop	few loops	many loops (group and individual model building)
Understanding dynamic behavior	linear behavior, all exogenous variables	exponential behavior, mostly exogenous variables	exponential behavior, s-shaped behavior, some endogenous variables	various behaviors, mostly endogenous variables
Differentiating types of flows and variables	one stock	two stocks	many stocks	many stocks
Using conceptual models	behavior over time graph with one variable, stock-flow diagram of the variable in the graph (variable as stock)	behavior over time graph with two variables, stock-flow diagram of the variable in the graphs (variables as stocks), causal loop diagram of the two stocks	behavior over time graph with many variables, stock-flow diagram of the variable in the graphs (variables as stocks or flows), causal loop diagram of the stocks in the s-f diagram	behavior over time graph with many variables, stock-flow diagram of the variable in the graphs (variables as stocks or flows), causal loop diagram of the elements in the s-f diagram
Creating simulation models	no quantitative modeling	simple arithmetic operations using system dynamics simulation software	quantitative models with feedback having one stock	quantitative models with feedback having many stocks
Testing policies	talking about what-if questions on behavior over time graphs and stock-flow diagrams	formulating problems with SD software and testing different scenarios by changing exogenous variables	simple structural changes in quantitative models and observing the results	structural changes in quantitative models and comparing the results, recommending policies

Chapter 3

Methodology

This study aims to investigate the impact of system dynamics tools on the comprehension of linear equations in the 8th grade secondary school mathematics course. The research questions for this study are:

1. Is there a significant difference in the mathematical achievement scores related to linear equations, which are part of the algebra unit, between the experimental group and the control group students after the experimental process?
2. Is there a correlation between the scientific achievement test results of the experimental group students and their system dynamics comprehension test results?
3. How does teaching mathematics using the System Dynamics approach affect eighth-grade students' attitudes towards linear equations?

3.1 Research Design

The study employed a two-group posttest design, with one group serving as the control and the other as the experimental group. Statistical analyses were conducted on the scores obtained from the post-test instruments. To support the findings, the researcher conducted interviews with students from both groups whose solutions were not understood or interpreted due to low processing in the scientific achievement post-test and the dynamics of the cognitive system post-test. Ericsson and Simon (1993) argue that the Think Aloud Protocol they used enables students to articulate their thoughts out loud while solving problems, allowing researchers to gain insights into students' cognitive processes. In this study, students were asked to explain the methods they used to solve the questions and their purposes using the think-aloud method after the tests. The aim was to obtain information about the cognitive processes of students whose solutions were not clearly understood or did not show the procedural steps. This method also supported obtaining more reliable results. The study's process map for data collection and analysis is provided below.

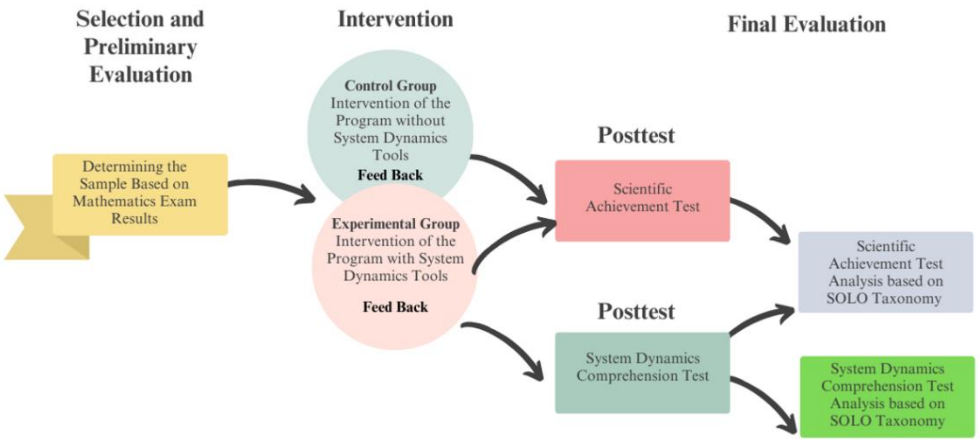

Figure 14. The process map of the data collection and data analysis.

3.2 Study Group

The study's target population is eighth-grade students enrolled in a foundation school in Sarıyer/İstanbul. The school study conducted is a boarding school that admits students through an exam. The students come from various provinces of Turkey.

Additionally, the study utilizes the Stella Online application as a simulation program, which requires students to use a tablet or computer during each session. The school where the research was conducted teaches with tablets, and each student has a personal tablet. The study involved a control group and an experimental group, each comprising 22 participants. The school has three classes with similar math grade point averages (GPAs) and one class with students who have higher math GPAs. For this study, classes 8C and 8D with similar GPAs were chosen. The math GPA of the control group, class 8D, was 79.57 (sd=12.69), while that of class 8C was 79.30(sd=11.0). The researcher selected class 8C as the experimental group because it had a more suitable mathematics lesson program. A total of 44 students, consisting of 26 boys and 18 girls aged 13-14 years, participated in the study. There were 13 boys and 9 girls in each group.

The scientific information obtained during the study was only used in scientific publications and academic presentations by the researchers. Information obtained from participants was not shared with anyone outside the research team. Permission was obtained from the students, their parents, and the school administration before conducting the study with the students.

3.3 Researcher's Role

In the fall semester of 2023-2024, the researcher implemented a study on both the control and experimental groups of students. The lesson plans, previously designed with the System Thinking Association and applied at different levels, were reorganized by the researcher to fit the 8th grade level. The experimental group received the modified lesson plans, which were applied for four days, with two hours of lessons each day. Post-test applications were made on the fifth day, and the study was completed in a total of nine lesson hours. The students received an introduction lesson to the Stella Online application, which was included in the nine hours. The control group encountered environmental problems in the form of problem questions without using the Stella Online application. The plans were implemented for a total of 5,5 lesson hours over 3 days, with 2 lesson hours each day, for the control group students. The post-test was administered during the first 20 minutes of the 6th hour. The 3.5-hour difference between the two groups is attributed to the introductory lesson on the use of the digital application Stella Online, the process of creating digital models and graphics during the applications, and the administration of the 'System Dynamics Comprehension Test' scale to the experimental group.

Both groups began the topic with a study of the depth of the Aral Lake, connecting linear equations to daily life. The students were shown videos and visuals depicting the change in the lake's depth over the years as a warm-up for the lesson. The researcher conducted the activities in the lesson plans and guided in-class discussions. As the researcher worked with both groups for the first time, she observed the class carefully. At the beginning of each lesson, she would take notes and review any points that she believed were not fully comprehended in the previous lesson.

3.4 Data Collection

The objective of this study is to examine the impact of system dynamics tools on the understanding and comprehension skills of 8th grade students regarding linear equations. The control and experimental groups were administered scientific achievement tests on linear equations as a data collection tool, while the experimental group was given system dynamics comprehension tests. Post-test questions and data analysis were selected using SOLO Taxonomy. This section provides a detailed account of the data collection and analysis methods employed in the study.

3.4.1 Data collection instruments. This section presents the scientific achievement test utilized as a post-test in the data collection process, the test for understanding system dynamics, and a detailed description of the SOLO Taxonomy employed in data collection and analysis. The SOLO taxonomy is a structure employed in the creation of the SAT test and in the analysis of test results. As the SOLO taxonomy is also emphasized in the explanation of the details of the test, this section will first explain the SOLO taxonomy and then proceed to explain the tests in detail.

3.4.1.1 SOLO taxonomy. SOLO (Structure of the Observed Learning Outcome) Taxonomy is a hierarchical structure consisting of five levels. It was developed by Biggs and Collis in 1982 to explain the structure of observable learning outcomes (Mulbar, Rahman & Ahmar, 2017). In SOLO taxonomy, the quality and structure of students' answers to questions are evaluated to assess their thinking processes regarding a specific topic (as cited in Biggs & Collis, 1989). The answers are analyzed based on predetermined criteria to determine the level of comprehension. As the level increases, the quality of versatile thinking and learning also increases. The first three levels of the taxonomy correspond to surface learning, while the last two levels are associated with deep learning (Biggs, Tang & Kennedy, 2022).

The aim of the research is to measure students' comprehension of linear equations using system dynamics tools and scales. System dynamics is a methodology that enables us to identify the components of a system and the connections between them, and to approach events from a holistic perspective

(Richmond & Peterson, 2001). Upon analyzing the SOLO Taxonomy steps, it becomes apparent that the steps are based on either existing or non-existing relationships. For instance, the unistructural and multistructural steps do not have any relationship, but the relational step mentions the relationship of information. Thus, the SOLO Taxonomy steps can aid in evaluating applications created with the systems thinking approach (See Table 4). Additionally, according to Biggs and Collis (1982), cognitive response progresses from simple to abstract, and the SOLO Taxonomy was developed based on this theory. The SOLO Taxonomy's hierarchical structure enables more effective measurement of students' cognitive levels. The identified verbs for each level of the taxonomy aid in writing clear and concise learning outcomes (Biggs, Tang & Kennedy, 2022). Analyzing scale questions with these verbs further simplifies the process. Additionally, İlhan and Gezer (2017) has found that the SOLO taxonomy is a more effective tool for measuring students' cognitive levels than Bloom's taxonomy, which has a similar approach (İlhan & Gezer, 2017). For these reasons, the study preferred the use of SOLO Taxonomy in its evaluation. The model supports the relationship between system dynamics and the SOLO taxonomy (Figure 15).

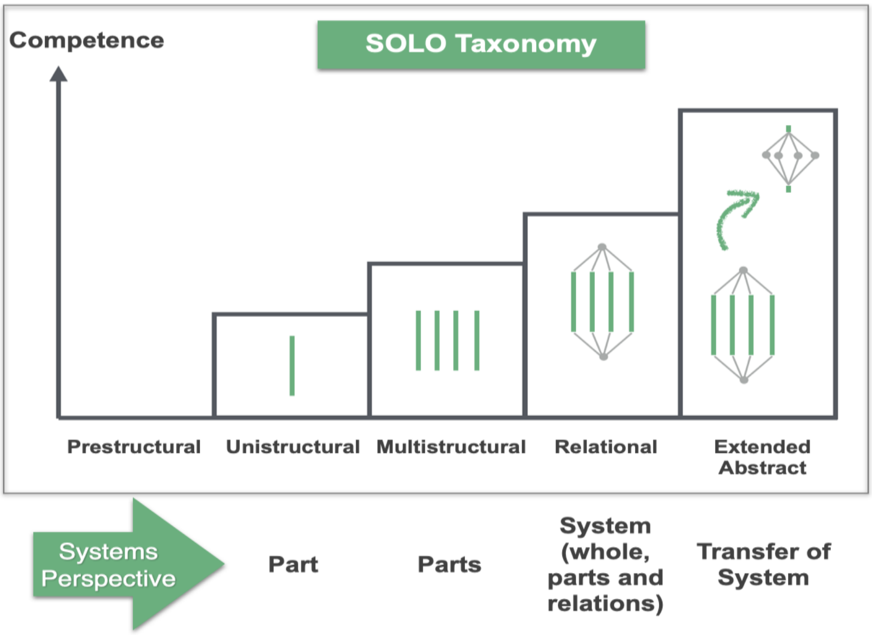

Figure 15. Alignment of SOLO taxonomy with systems thinking (Systems Thinking Association, 2024).

3.4.1.2 The scientific achievement test. The researcher created the Scientific Achievement Test (SAT) to assess the post-test of the experimental and control group students on linear equations, taking into account the learning outcomes in the mathematics curriculum (MoNE, 2018). The test questions were selected from the multiple-choice questions under the title of 'Contextual Problems' shared on the website of the Ministry of National Education and were applied as open-ended questions by deleting the choices (MoNe, 2022).The table (3.4.1) below provides a detailed explanation for the selection of questions in the post-test from the contextual problems prepared by the Ministry of National Education. In addition, similar linear equation questions measuring the same skills were included in the lesson plan and solved during class. Two of the four selected questions were modified to become higher-level questions according to the SOLO taxonomy. The test asked for the process steps in response to the questions. The scientific achievement test consisted of four questions and was completed in 20 minutes. Details about the objectives and sub-items can be found in Table 2. The questions for the scientific achievement test are located in Appendix A. The reliability and validity of this test are detailed in the findings, which can be found on page 54.

Table 2

Outcomes Corresponding to the Questions in the Scientific Achievement Test

Question	**Outcomes**	**Reason for Selection**	**Solo Taxonomy Level**
1	M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation. M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.	This question evaluates the ability to interpret two distinct graphs with varying data and identify the correlation between them.	0 – 4 (No Score-Extended Abstract)

Tablo 2 (cont.d)

Question	Outcomes	Reason for Selection	Solo Taxonomy Level
2a	M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation. M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.	In this question, the skill of expressing the heights of balloons changing over time on a graph with a linear equation is measured.	0 - 3 (No Score - Relational)
2b	M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.	For this task, students are required to interpret the balloons on the same graph in relation to each other and determine a general term based on the difference between them.	0 - 4 (No Score - Extended Abstract)
3	M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.	In this question, the student is expected to read the time when the change in money spent and the change in money remaining over time are equalized on the graph.	0 - 3 (No Score - Relational)
4a	M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation. M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.	This question requires the reader to interpret a graph displaying the toner levels and number of shots for two photocopiers. The question assesses the ability to follow multiple processes and establish relationships between variables. Additionally, the reader must calculate fees by establishing a proportion with the given information.	0 - 3 (No Score - Relational)

Table 2 (cont.d)

Question	Outcomes	Reason for Selection	Solo Taxonomy Level
4b	M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation.	Using the provided information, it is necessary to compare the two machines and select the preferred option based on the given criteria.	0 – 3 (No Score - Relational)

3.4.1.3 The system dynamics comprehension test. The System Dynamics Comprehension Test (SDT) was administered as a post-test to measure the experimental group students' understanding of the basic concepts of system dynamics. SDT was originally designed by Hasret Nuhoğlu (2007) for her doctoral dissertation (2007) and was restructured and applied by the researcher in accordance with her own study. The test consists of six questions. The first five questions include various question types, such as multiple choice, fill-in-the-blank, model and graph construction, and model completion. Question 6 is an open-ended inquiry that solicits feedback from students regarding the most significant aspect of mathematics lessons that incorporate system dynamics tools (See Appendix B). The purpose of this question is to collect data that can be utilized to enhance future implementations. The SDT was piloted with two 9th grade students who had previously worked with system dynamics tools in various fields, including mathematics and science. The instructions for the questions were reorganized based on the students' feedback.

The researcher organized the objectives of the questions in the test before the application. Expert opinion was sought to ensure compatibility between the objectives and the questions, resulting in the final version of the objectives. Prior to implementation, a Test Blueprint was created for the System Dynamics Comprehension Test using both Bloom's Taxonomy (Bloom, 1956) and SOLO Taxonomy (Biggs, 1999). The objectives of the questions in the System Dynamics

Comprehension Test were aligned with the sections in this taxonomy. Table 3 and Table 4 are located below.

Table 3

Bloom's Revised Taxonomy

Learning Objectives	Remember	Understand	Apply	Analyze	Evaluate	Create
Identify the concept of stock, which is one of the fundamental tools of System Dynamics. Choose stock over other tools.	Define, describe, draw, find, **identify**, label, list, match, name, quote, recall, recite, tell, write	**Classify**, compare, conclude, demonstrate, discuss, exemplify, explain, identify, illustrate, interpret, paraphrase, predict, report	Apply, change, **choose**, compute, dramatize, implement, interview, prepare, produce, role play, select, show, transfer, use	Analyse, characterize, classify, compare, contrast, debate, deconstruct, deduce, differentiate, discriminate, distinguish, examine, organize, outline, relate, research, separate, structure	Appraise, argue, assess, choose, conclude, critique, decide, evaluate, judge, justify, monitor, predict, prioritize, prove, rank, rate, select	Compose, construct, create, design, develop, generate, hypothesize, invent, make, perform, plan, produce
Relate the connections between the basic tools of system dynamics, stocks and behaviour graphs over time	Define, describe, draw, find, identify, label, list, match, name, quote, recall, recite, tell, write	Classify, compare, conclude, demonstrate, discuss, exemplify, explain, identify, illustrate, interpret, paraphrase, predict, report	Apply, change, choose, compute, dramatize, implement, interview, prepare, produce, role play, select, show, transfer, use	Analyse, characterize, classify, compare, contrast, debate, deconstruct, deduce, differentiate, discriminate, distinguish, examine, organize, outline, **relate**, research, separate, structure	Appraise, argue, assess, choose, conclude, critique, decide, evaluate, judge, justify, monitor, predict, prioritize, prove, rank, rate, select	Compose, construct, create, design, develop, generate, hypothesize, invent, make, perform, plan, produce
Design a model consisting of stocks and flows in the Stella Online program and draw the behavior graph over time.	Define, describe, draw, find, identify, label, list, match, name, quote, recall, recite, tell, write	Classify, compare, conclude, demonstrate, discuss, exemplify, explain, identify, illustrate, interpret, paraphrase, predict, report	Apply, change, choose, compute, dramatize, implement, interview, prepare, produce, role play, select, show, transfer, use	Analyse, characterize, classify, compare, contrast, debate, deconstruct, deduce, differentiate, discriminate, distinguish, examine, organize, outline, relate, research, separate, structure	Appraise, argue, assess, choose, conclude, critique, decide, evaluate, judge, justify, monitor, predict, prioritize, prove, rank, rate, select	Compose, construct, create, **design**, develop, generate, hypothesize, invent, make, perform, plan, produce
Relate the connections between the concepts of stocks and flows, interpret the states of change.	Define, describe, draw, find, identify, label, list, match, name, quote, recall, recite, tell, write	Classify, compare, conclude, demonstrate, discuss, exemplify, explain, identify, illustrate, **interpret**, paraphrase, predict, report	Apply, **change**, choose, compute, dramatize, implement, interview, prepare, produce, role play, select, show, transfer, use	Analyse, characterize, classify, compare, contrast, debate, deconstruct, deduce, differentiate, discriminate, distinguish, examine, organize, outline, **relate**, research, separate, structure	Appraise, argue, assess, choose, conclude, critique, decide, evaluate, judge, justify, monitor, predict, prioritize, prove, rank, rate, select	Compose, construct, create, design, develop, generate, hypothesize, invent, make, perform, plan, produce
Relate the connections between the basic tools of system dynamics, tocks, flows, and factors in the given model.	Define, describe, draw, find, identify, label, list, match, name, quote, recall, recite, tell, write	Classify, compare, conclude, demonstrate, discuss, exemplify, explain, identify, illustrate, interpret, paraphrase, predict, report	Apply, change, choose, compute, dramatize, implement, interview, prepare, produce, role play, select, show, transfer, use	Analyse, characterize, classify, compare, contrast, debate, deconstruct, deduce, differentiate, discriminate, distinguish, examine, organize, outline, **relate**, research, separate, structure	Appraise, argue, assess, choose, conclude, critique, decide, evaluate, judge, justify, monitor, predict, prioritize, prove, rank, rate, select	Compose, construct, create, design, develop, generate, hypothesize, invent, make, perform, plan, produce

Table 4

SOLO Taxonomy

Learning Objectives	Unistructural	Multistructural	Relational	Extended abstract
Identify the concept of stock, which is one of the fundamental tools of System Dynamics. Choose stock over other tools.	Memorize, **identify**, recognize, count, define, draw, find, label, match, name, quote, recall, recite, order, tell, write, imitate	Classify, **describe**, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate	Apply, integrate, analyse, explain, predict, conclude, summarize (précis), review, argue, transfer, make a plan, characterize, compare, contrast, differentiate, organize, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, solve a problem	Theorize, hypothesize, generalize, reflect, generate, create, compose, invent, originate, prove from first principles, make an original case, solve from first principles
Relate the connections between the basic tools of system dynamics, stocks and behaviour graphs over time	Memorize, identify, recognize, count, define, draw, find, label, match, name, quote, recall, recite, order, tell, write, imitate	Classify, describe, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate	Apply, **integrate**, analyse, explain, predict, conclude, summarize (précis), review, argue, transfer, make a plan, characterize, compare, contrast, differentiate, organize, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, solve a problem	Theorize, hypothesize, generalize, reflect, generate, create, compose, invent, originate, prove from first principles, make an original case, solve from first principles
Design a model consisting of stocks and flows in the Stella Online program and draw the behavior graph over time.	Memorize, identify, recognize, count, define, draw, find, label, match, name, quote, recall, recite, order, tell, write, imitate	Classify, describe, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate	Apply, integrate, analyse, explain, predict, conclude, summarize (précis), review, argue, transfer, make a plan, characterize, compare, contrast, differentiate, organize, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, **solve a problem**	Theorize, hypothesize, generalize, reflect, generate, **create**, compose, invent, originate, prove from first principles, make an original case, solve from first principles
Relate the connections between the concepts of stocks and flows, interpret the states of change.	Memorize, identify, recognize, count, define, draw, find, label, match, name, quote, recall, recite, order, tell, write, imitate	Classify, describe, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate	Apply, integrate, **analyse**, **explain**, predict, conclude, summarize (précis), review, argue, transfer, make a plan, characterize, compare, contrast, differentiate, organize, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, solve a problem	Theorize, hypothesize, generalize, reflect, generate, create, compose, invent, originate, prove from first principles, make an original case, solve from first principles
Relate the connections between the basic tools of system dynamics, stocks, flows, and factors in the given model.	Memorize, identify, recognize, count, define, draw, find, label, match, name, quote, recall, recite, order, tell, write, imitate	Classify, describe, list, report, discuss, illustrate, select, narrate, compute, sequence, outline, separate	Apply, integrate, **analyse**, **explain**, predict, conclude, summarize (précis), review, argue, transfer, make a plan, characterize, compare, contrast, differentiate, organize, debate, make a case, construct, review and rewrite, examine, translate, paraphrase, solve a problem	Theorize, hypothesize, generalize, reflect, generate, create, compose, invent, originate, prove from first principles, make an original case, solve from first principles

3.4.2 Data collection procedures. The study selected students from two classes of 8th grade students in a private foundation school during the fall semester of the 2023-2024 academic year as the experimental and control groups. The experimental group was taught the subject of 'Linear Equations' using system dynamics tools, while the control group was taught without the use of such tools. The aim of this study was to determine if there was a significant difference in the use of system dynamics tools between the two groups. Table 5 summarizes the content and duration of the lessons with the students.

Table 5

Lesson Plans Implemented with Experimental and Control Group Students

Lessons	**Experimental Group Lesson Plan**	**Lesson Hours (40')**	**Lessons**	**Control Group Lesson Plan**	**Lesson Hours (40')**
Lesson 1	Stella Online Introduction Course	50'			
Lesson 2	Introduction to Linear Equations: Changes in Aral Lake Depth Over Time	80'	Lesson 1	Introduction to Linear Equations: Changes in Aral Lake Depth Over Time	60'
Lesson 2	Water Level Changes in Istanbul's Dams Over Time	40'			
Lesson 4	Changes in Carbon Emissions Over Time	40'			
Lesson 5	Basic Level Linear Equations Problems	60'	Lesson 2	Water Level Changes in Istanbul's Dams Over Time + Basic Level Linear Equations Problems	80'
Lesson 6	Contextual Linear Equations Problems	50'	Lesson 3	Contextual Linear Equations Problems	40'

Table 5 (Cont.d)

Lessons	**Experimental Group Lesson Plan**	**Lesson Hours (40')**	**Lessons**	**Control Group Lesson Plan**	**Lesson Hours (40')**
Lesson 7	Post-Tests (Scientific Achievement Test and System Dynamics Comprehension Test)	20' + 20'	Lesson 4	Post-Test (Scientific Achievement Test)	20'
	Total Lesson Hours	**9 lesson hours**		Total Lesson Hours	**5 lesson hours**

The table above indicates that the experimental group practiced for 9 lesson hours, while the control group practiced for 5 lesson hours. The difference in course hours can be attributed to the following reasons:

- An introduction course on Stella Online was conducted with the experimental group students for one class hour. The lesson covered basic information about the systems thinking approach and the technical features of the Stella Online application.
- During the lesson plans for Lake Aral, Istanbul's Dams, and Carbon Emissions, students used the Stella Online application to model the problems. The use of models extended the lesson time, but also helped to solve the problems.
- In addition to the scientific achievement test, the experimental group students were given a system dynamics comprehension test as a post-test.

3.4.2.1 Intervention programme. The implementation with the experimental group lasted for 9 hours and with the control group lasted for 5 hours is described in detail below. Prior to the Stella Online Introduction lesson, students were contacted via email and requested to register for the Stella Online application.

3.4.2.1.1 Stella Online introduction course. Stella Online Introduction course is implemented only with the experimental group. The researcher presented the systems thinking approach in a 10-minute session. The presentation included basic information about systems thinking and its application in education. Afterward, the students were instructed to open the Stella Online application to learn about system dynamics tools. Together, the students modeled the 'Water in the Bathtub' problem using the Stella Online application (Systems Thinking Association, n.d).

3.4.2.1.2 Introduction to linear equations: Changes in Aral Lake depth over time. To pique students' interest in environmental issues and raise their awareness of the impact of human activity on the environment, the lesson began with a news video about the reduction in the depth of Lake Aral since 1960. The presentation introduced the concept of a linear relationship by analyzing the change in the lake's depth over time. Tables, equations, and graphs were created to illustrate the change in the depth of Lake Aral between 1960 and 1970. The discussion included the dependent and independent variables. The following questions were posed to the students:

Problem 1: In 1960, Lake Aral had a depth of 5500 centimeters. However, due to drying, the lake's depth has been decreasing by an average of 50 centimeters per year. Based on this information;

- Complete the table with the change in depth of Lake Aral between 1960 and 1970 and write the corresponding equation.
- Use ordered pairs to express the data from the table and plot them on the graph.
- Analyze the resulting graph by connecting the points and identifying.
- Write the dependent and independent variables.

The questions above were answered with the students on the board. The students in the control group proceeded to work on Problem 2 after completing this section. In contrast, the students in the experimental group followed a different process:

Upon opening the Stella Online application, students were prompted to create a stock-flow diagram and its corresponding graph to interpret the change in the depth of Lake Aral over time. The application required students to complete the following questions:

- Create the model and graph in the Stella Online application.
- In 2023, determine the depth of Lake Aral in centimeters.

- Based on the graph, determine the projected timeline for the complete depletion of Lake Aral.

Following Problem 1, students were allotted time to solve Problem 2. The researcher provided assistance to students who encountered difficulties. The details of Problem 2 are provided below:

Problem 2 : In 1913, the total area of cotton fields cultivated in Uzbekistan was 3000 km^2. From 1913 to 1990, this area increased by 240 km^2 per year. Accordingly,

- The task is to complete a table and create an equation that represents the changes in cotton production in Uzbekistan from 1913 to 1990.
- Use ordered pairs to express the data presented in the table.
- Display the resulting ordered pairs on the graph and analyze the graph that is formed when connecting the points.
- Write the dependent and independent variables.

Both groups answered Problem 2 with guidance from the researcher. The control group concluded with a wrap-up, while the experimental group used the Stella Online application to model the question below.

- The model and graph should be created using the Stella Online application.

At the conclusion of the lesson, students in the experimental group were requested to provide feedback via a Google Form. The form consisted of two questions: “List two things you learned in today's lesson' and 'If there is an area that needs improvement in today's lesson, please share your opinion.”. Some students suggested that the application was slow when creating a model, so more time should be allocated for this task. Consequently, the model building time was increased for the next lesson.

3.4.2.1.3 Water level changes in Istanbul's dams over time. The experimental group students followed the plan outlined below. Meanwhile, the control group students completed Problem 1 and Problem 2 questions in the “Istanbul’s Dams” plan, which was included in the “Basic Level Linear Equations Problems” worksheet.

To review the previous lesson, the instructor began by asking the students what they recalled about Lake Aral. The lesson covered the concepts of linear relationships, dependent and independent variables, stock, flow, and factor. Following this, the lesson plan titled 'Istanbul's Dams' was presented.

The discussion revealed that the water levels in the dams have decreased over the years due to various reasons. During the presentation, students were shown visuals depicting the current state of water in Istanbul's dams and were asked to interpret the information. The students were then presented with a problem question regarding the change in water levels between 2010 and 2020 and were asked to answer related questions.

Problem 1: In 2010, the dams in Istanbul held 2120 m^3 of water. On average, these dams are filled with 790 million m^3 of water each year from precipitation. In the same year, Istanbul consumed 810 million m^3 of water. Based on this information;

- A table depicting the change in water levels in Istanbul's dams between 2010 and 2020, along with the corresponding equation, was created.
- The model and graph were generated using the Stella Online application.
- It was determined how much water would remain in the dams if the same consumption rate of 810 million m^3 per year continued until 2020.

The researcher gave the students time for Problem 1, during which time she walked around the classroom and guided the students. It was interpreted with the students that the water in the dams of Istanbul decreased linearly over the years. Then Problem 2 was given to the students:

Problem 2: In 2010, the dams in Istanbul held 2120 m^3 of water. On average, 790 million m^3 of water is added to the dams each year through precipitation. In 2010, Istanbul consumed 810 million m^3 of water annually. From 2010 to 2020, water consumption increased by 31 million m^3 per year. Based on this information;

- A table depicting the change in Istanbul's water consumption between 2010 and 2020 and the corresponding equation has been created.
- Create the model and graph in Stella Online application.
- Find the year in which Istanbul's dams will run out of water.

In Problems 1 and 2, we compared models with the students. In Problem 2, we discussed the model of water in Istanbul's dams, which does not decrease linearly but rather incrementally as water consumption constantly increases. This helped students better understand the difference between linear and nonlinear graphs. We also shared with them that the real data is much closer to the non-linear graph.

At the conclusion of the lesson, the experimental group students were provided with a Google Form containing identical questions to those in the previous lesson. The purpose of this was to obtain feedback on the lesson. No suggestions for improving the course were provided by any of the students.

3.4.2.1.4 Changes in carbon emissions over time. This lesson plan was only applied to the experimental group of students. Its aim is to help students establish a better connection between stocks, flows, and change over time graphs, which are system dynamics tools, and to improve their understanding of the factors that affect stocks and flows. Therefore, after the introduction to the lesson, the students constructed a stock-flow diagram with the climate crisis as a stock, without numerical data. To maintain students' interest in the lesson, it began with a video titled 'Extinction of a Species'. Following the video, the discussion shifted to the impact of fossil fuels on the climate crisis. Following the video, the discussion shifted to the impact of fossil fuels on the climate crisis. Students were given the opportunity to express their opinions on the factors contributing to the crisis, revealing that carbon emissions are a direct cause.

Following that, the influence of the Industrial Revolution was discussed with the students throughout the presentation, leading to an imbalance in carbon emissions. Prior to the lecture, the researcher structured the carbon emission graphs of Germany and the rest of the world in a linear fashion to approximate the actual statistics. Students were given global and German carbon emission graphs during the lesson, and they were asked to analyze the changes (Figure 16). Next, using the Stella Online application modeling was carried out with students based on the graphics.

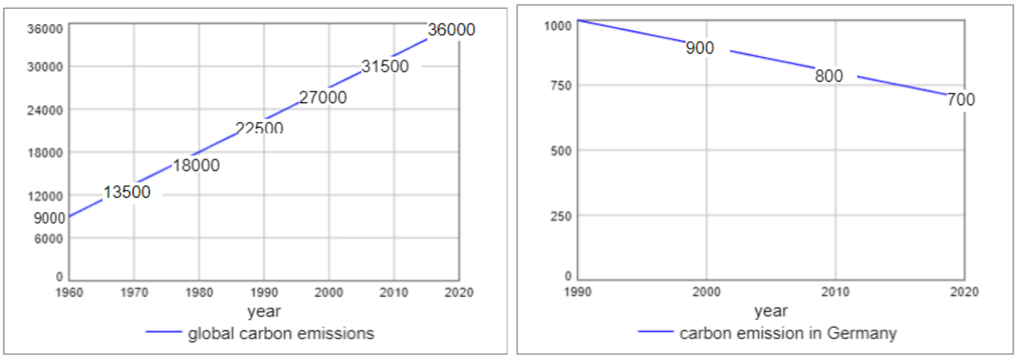

Figure 16. Global carbon emissions (left) and carbon emission in Germany (right).

Students looked over the provided graphs and their own models at the conclusion of the class. There was discussion of the causes of both the global rise in carbon emissions and the decline in carbon emissions in Germany. The inflow in the global carbon emission model and the output flow in the German carbon emission model's graphs were changed, allowing students to make connections between them.

3.4.2.1.5 Basic level linear equations problems. For Experimental Group Students : A worksheet was created that contains 14 open-ended, fill-in-the-blank, and multiple-choice questions on the subject of linear equations, selected from the students' mathematics textbooks. The first question was solved on the board as a reminder, and then students were given time to solve the remaining questions. At the end of the time limit, students were given the opportunity to solve the questions on the board. Each question was solved, and the correct solutions were made visible to all students.

For Control Group Students: In this worksheet, the control group students, in addition to the experimental group students, completed Problem 1 and Problem 2 that the experimental group students solved in the "Istanbul's Dams" lesson plan without using the Stella Online application. They discussed the reasons for the decrease in water levels in Istanbul's dams. It was explained that the problems were based on real data.

3.4.2.1.6 Contextual problems. A worksheet consisting of six contextual questions on linear equations, along with questions from previous years, was shared on the website of the Ministry of National Education. Each student was given time to solve the questions individually. Afterwards, the students were given the opportunity to present their solutions on the board and compare them with the correct answers. In the worksheet of the experimental group, the researcher added a link to two questions modeled in the Stella Online application before the lesson, which was not present in the control group's worksheet. The aim was to help the students better understand the questions by using the model to solve the problems. Experimental students benefited from the shared model in solving two questions.

3.4.2.2 Implementation of the post-tests. At the start of the lesson, the experimental group students were informed that they would take the Scientific Achievement Test and the System Dynamics Comprehension Test, while the control group students would only take the Scientific Achievement Test. They were instructed that the tests were not graded, so they need not worry. During the test, they were asked to note down all their thoughts about the questions. The tests were administered with a time limit of 20 minutes each, and collected upon completion. The experimental group was given a 5-minute break between the two tests. After the break, the second post-test was distributed and another 20 minutes were allotted for completion, after which the papers were collected. All students completed the tests without issue.

3.4.3 Data Analysis Procedures. The study analyzed the mathematics exam averages of the experimental and control groups during the fall semester of the 2023-2024 academic year as a pre-test. After the experiment, the scientific achievement test was administered to both groups, while the experimental group students also took the system dynamics comprehension test as a post-test. This section provides detailed information about the data analysis.

3.4.3.1 Analysis of the scientific achievement test. Prior to the application, the mathematics exam averages of the experimental and control groups for the fall semester of 2023-2024 were accepted as pretests and analyzed. The independent sample t-test was run in the SPSS program, revealing no significant difference between the two groups. Therefore, it was concluded that the two groups had equal achievement level (The"Findings" section provides a detailed account of the results.).

The scientific achievement test includes four open-ended questions, two of which require higher thinking skills based on the SOLO Taxonomy. The questions were evaluated using the four steps of the SOLO Taxonomy: Unistructural, Multistructural, Relational, and Extended Abstract. The researcher used a rubric to examine the relationship between each step taken by the students and the steps in the SOLO Taxonomy. The language used is clear, concise, and objective, adhering to formal register and avoiding biased or ornamental language. The text is grammatically correct and follows conventional academic structure and formatting. Each question was scored on a scale of 0 to 4. If the students' solutions were unclear, interviews were conducted to better understand their thought process before scoring.

The scientific achievement test scores of the experimental and control groups were analyzed using an independent t-test in the SPSS program to determine if there was a significant difference between the averages.

3.4.3.2 Analysis of the system dynamics comprehension test. The experimental group students underwent a post-test on their comprehension of system dynamics. The test consisted of six questions, five of which assessed their logic and use of system dynamics tools. The final question asked for their evaluation of the mathematics lessons taught with system dynamics.

The evaluation of the system dynamics comprehension test was based on the SOLO Taxonomy, as used in scientific achievement tests. The researcher used a rubric to associate student answers with the steps of the SOLO Taxonomy and score each question between 0 and 4.

A correlation test analysis was performed in the SPSS program to determine if there is a relationship between the scientific achievement test results and the system dynamics comprehension test results.

3.4.3.3 Content analysis of the students' attitudes towards linear equations. In the final question of the System Dynamics Comprehension Test, administered to the experimental group as a posttest, students were asked to evaluate the contribution of teaching mathematics with system dynamics tools. Based on their responses, the impact of system dynamics tools on mathematics lessons was assessed.

3.4.4 Reliability. The reliability of a measurement tool refers to its ability to consistently measure the intended variable or produce error-free results (Klassen et al., 2012).

The study's statistical analyses were conducted by the researcher, with regular feedback provided by an expert engineer from the Systems Thinking Association. The solutions of students who used different methods than those in the rubric were evaluated alongside the expert's. Additionally, the practitioner conducted one-on-one interviews with students who provided unclear solutions, did not demonstrate clear steps, and utilized multiple solution methods. The practitioner asked the students to explain why and how they performed the operations on the test paper. The students' responses contributed to a more objective analysis, avoiding subjective evaluations such as 'the student may have adopted this way of thinking' based on the students' answers. In light of these considerations, the analysis was designed to mitigate potential biases.

Table 6 displays the item difficulty indices and discrimination indices of six items for the experimental group's scientific achievement test results (Ilhan & Gezer, 2018).

Table 6

Item Difficulty and Discrimination Index

	Item 1	Item 2a	Item 2b	Item 3	Item 4a	Item 4b
Item Difficulty	0.89	0.86	0.36	0.64	0.70	0.34
Item Discrimination	0.10	0.40	0.50	0.40	0.40	0.70

Upon examination of the table, it is evident that the test results exhibit a range of difficulty levels, with both challenging and straightforward items. The questions are arranged in order of difficulty, allowing for a suitable analysis. The first question, Item 1, was predicted to be answered correctly by the majority of students, and the actual result was in line with this prediction. Items 2a, 3, and 4a showed moderate discrimination, while the most discriminative items were Items 2b and 4b.

Items 2b and 4b are items that require skills at the relational and extended abstract levels of the SOLO Taxonomy and were added by the practitioner as a second option to two of the conceptual questions. The reason for adding these options was to deepen the question and to see the student's ability to make relationships and generalizations.

3.4.5 Validity. Joppe (2000) explains what is meant by validity in quantitative research as follows:

“Validity determines whether the research truly measures that which it was intended to measure or how truthful the research results are” (p.1).

The sections below outline the study's internal and external consistencies.

3.4.5.1 Internal validity. This study is a robust experimental study because it includes both an experimental group and a control group. Students in the experimental group and the control group are at the same level, and both classes' average grades on the mathematics exam are quite similar.

The lesson plans, previously implemented in other levels and classes, were revised by the researcher to fit their own subject and level. Three contextual questions from the website of the Ministry of National Education and one from the high school entrance exam were selected for the Scientific Achievement Test scale. The researcher included additional items in the two contextual questions to provide more depth. Expert opinions from the Systems Thinking Association were obtained for all lesson plans to be implemented with the students. Both scales were solved by two 9th grade students from the same school who had experience with system dynamics tools prior to the application. Feedback was received on the instructions, which were organized based on the students' feedback.

Given that the topic of linear equations represented a novel experience for students, it was deemed inappropriate to administer a pretest. Bias in data collection was eliminated by using the same researcher to collect data for both groups. Both classes have the same number of students. The applications and post-tests were completed by every student in the classes. Students without a background in systems thinking courses make up both groups. Conflict could occur if the same researcher scores the data while the data is being analyzed. For this reason, the scientific accomplishment test is scored using the Solo Taxonomy steps in order to ensure greater impartiality in scoring.

The SOLO Taxonomy was developed by Biggs and Collis in 1982 to clarify the structure of observable learning outcomes (Mulbar, Rahman & Ahmar, 2017). In order to obtain feedback on the taxonomy, John Burville Biggs, one of the creators of the SOLO Taxonomy, was contacted via email. Biggs provided feedback stating that the scores in the scientific achievement test were determined using the SOLO Taxonomy levels. The problematic question is included in Appendix C, along with John Biggs' evaluation.

> *Researcher:* "My general research question is, whether there is a relation between systems thinking and mathematical problem solving skills. I'm trying to find the effect of systems thinking on mathematical problem solving skills if there is any. For this, I selected some questions that seemed to require higher order thinking skills from exams of the Ministry of National Education for 8th grade students. I want to use SOLO taxonomy for evaluating the students' responses. For this, I did a pilot study with one of my students and made an interview (a think-aloud session) to see how she thinks when solving the problem. I took some notes of her reasoning. Based on these notes I tried to attach the verbs that are given as manifestations of SOLO stages to the part of the notes. Could you please let us know if we are on the right track? Additionally, any suggestions on how we can improve would be greatly appreciated."

> *John Burville Biggs:* "Yes, I believe you are on the right track. The verbs seem to have anchored your classifications appropriately . Nice work."

3.4.5.2 External validity. The study sample comprised 44 eighth-grade students enrolled in a foundation school. Convenience sampling was used in the study since it was carried out at the researcher's school. The research school admits students from various provinces of Turkey through an entrance exam. Although this may limit the generalizability of the results, the researcher did not select the control and experimental groups from the classes with the highest grade point averages in mathematics at the eighth grade level. Instead, the researcher selected classes with lower grade point averages. This may actually increase the generalizability of the results.

Additionally, students were instructed to utilize Stella Online, a no-cost simulation program, independently during the application process. Through this program, students generated stock-flow diagrams and graphs. As a result, it is advisable to provide each student with access to a computer or tablet during class hours. The study was conducted in a school that offered tablet training. In schools that lack tablets or computers, the logic of system dynamics tools can be implemented by drawing stock-flow diagrams on paper. This approach may have less impact on the generalizability of the application and results.

Chapter 4

Findings

Data were collected and analyzed based on the following research questions provided. This section will analyze the results of the performed tests.

1. Is there a significant difference in the mathematical achievement scores related to linear equations, which are part of the algebra unit, between the experimental group and the control group students after the experimental process?
2. Is there a correlation between the scientific achievement test results of the experimental group students and their system dynamics comprehension test results?
3. How does teaching mathematics using the System Dynamics approach affect eighth-grade students' attitudes towards linear equations?

In the study, to address the research questions, a scientific achievement test was administered to the experimental and control groups, and a system dynamics comprehension test was administered to the experimental group.

4.1 Results of the Pre-Scientific Achievement Test (SAT)

The selection of the experimental and control groups was based on the students' mathematics grade point averages for the fall semester of 2023-2024, which were analyzed and accepted as a pre-test. Table 7 contains the descriptive statistics results of the pre scientific achievement test.

Tablo 7

Descriptive Statistics Results of the Pre-SAT

		Min	Max	Mean	Std.	Sig.	Skewness	Kurtosis
Experimental group	22	61.50	95.00	79.57	11.00	0.07	-0.35	-1.30
Control group	22	49.50	96.50	79.30	12.69	0.12	-0.82	-0.05

Table 7 shows that both groups had 22 students. The experimental group (*M* = 79.57, *SD* = 11.0) had a minimum and maximum score of 61.5 and 95.0, respectively, while the control group (*M* = 79.30, *SD* = 12.69) had a minimum and maximum score of 49.5 and 96.5 on scientific achievement test, respectively.

The aim of this study was to investigate whether there was a significant difference between the pretests of the experimental and control group students. To achieve this, an independent samples t-test was conducted using the SPSS program. The stages of the application are summarized below.

Upon examining Table 7, it is evident that the Shapiro-Wilk test yielded significant values of 0.07 and 0.12. As both values exceed the alpha value of 0.05, it can be concluded that the distribution is normal. Additionally, the Skewness and Kurtosis values fall within the acceptable range of -2 to 2.

4.1.1 Independent samples t-test for the pre-SAT. An independent samples t-test was conducted to compare the average scores of the experimental group (*M* = 79.57, *SD* = 11.00) and the control group (*M* = 79.29, *SD* = 12.69). The t-test revealed no statistically significant difference between the groups ($t(42) = 0.47$, $p = 0.94$). The study found that the effect sizes were very small (Cohen's (1988) $d = 0.12$) indicating that there was no practically significant difference between the two groups. Table 8 contains the results of the pre scientific achievement test.

Table 8

Independent Samples t-test for the Pre-SAT

	Levene's Test		t-test			Confidence interval	
	F	Sig.	t	df	Sig.	Lower	Upper
Equal variances assume	0.23	0.63	0.08	42	0.94	-6.95	7.50
Equal variances not assumed				41.17	0.94	-6.96	7.50

Additionally, Levene's Test for equality of variances was run before interpreting the results of t testing. Because the significance value was greater than .05 in Levene's Test (.63), equal variances were assumed.

4.2 Descriptives Statistics of the Post-Scientific Achievement Test (SAT)

The scientific achievement test consisted of six items, including four open-ended questions, two of which had additional sub-items. The test was administered to both the experimental and control groups.

The test was scored based on the four levels of the SOLO Taxonomy: unistructural (1 point), multistructural (2 points), relational (3 points), and extended abstract (4 points). Table 9 displays the scoring table for the test. At the unistructural level of the SOLO Taxonomy, students comprehend only one aspect of the subject. At the multistructural level, students comprehend many related features but are unable to relate them to each other. At the relational stage, students can combine parts to form a coherent whole with meaning. In the extended abstract stage, students can generalize structures by considering new and abstract features. This represents a higher level of understanding (Biggs and Tank, 2011). The varying intervals between the questions are due to the measurement of skills at different levels. The maximum score achievable is 20 points, while the minimum is 0 points in the SAT.

Tablo 9

Scoring Table for the Post-SAT

Items	Item Score Interval
1	0 - 4 (No Score - Extended Abstract)
2a	0 - 3 (No Score - Relational)
2b	0 - 4 (No Score - Extended Abstract)
3	0 - 3 (No Score - Relational)
4a	0 - 3 (No Score - Relational)
4b	0 - 3 (No Score - Relational)

Table 10 shows that the experimental group students had a mean score of 13.4 (sd=4.15) while the control group students had a mean score of 9.27 (sd=3.43). The minimum and maximum scores for the experimental group were 4 and 19, respectively, and for the control group were 4 and 14. Figure 10 shows the completion rates for all questions.

Table 10

Descriptive Statistics Results of the Post-SAT

	N	Mean	Median	Std.	Min	Max
Experimental Group	22	13.41	14.50	4.25	4	19
Control Group	22	9.27	10.00	3.61	4	14

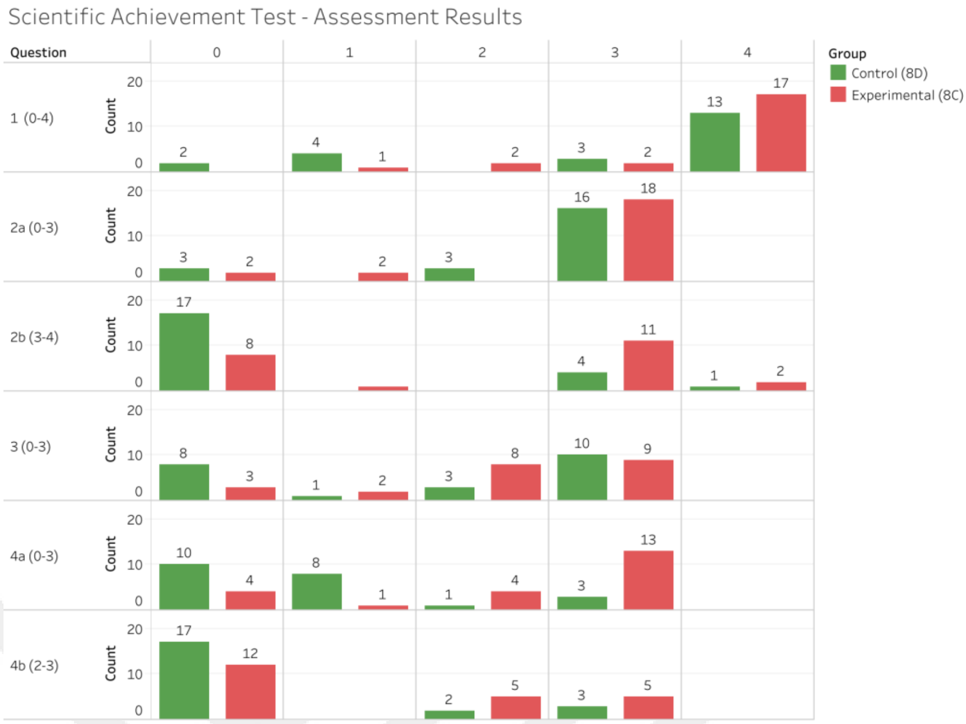

Figure 17. Completion rates for SAT.

When scoring the scientific achievement test, additional steps were taken to increase the reliability of the scoring. Students whose answers were not clearly understood were interviewed for 5 minutes each. During the interview, they were asked about the reasons for their actions in the related questions and were allowed to think aloud. The model below presents the average scores of the students interviewed from the experimental and control groups and compares them. All students with ambiguous responses were interviewed.

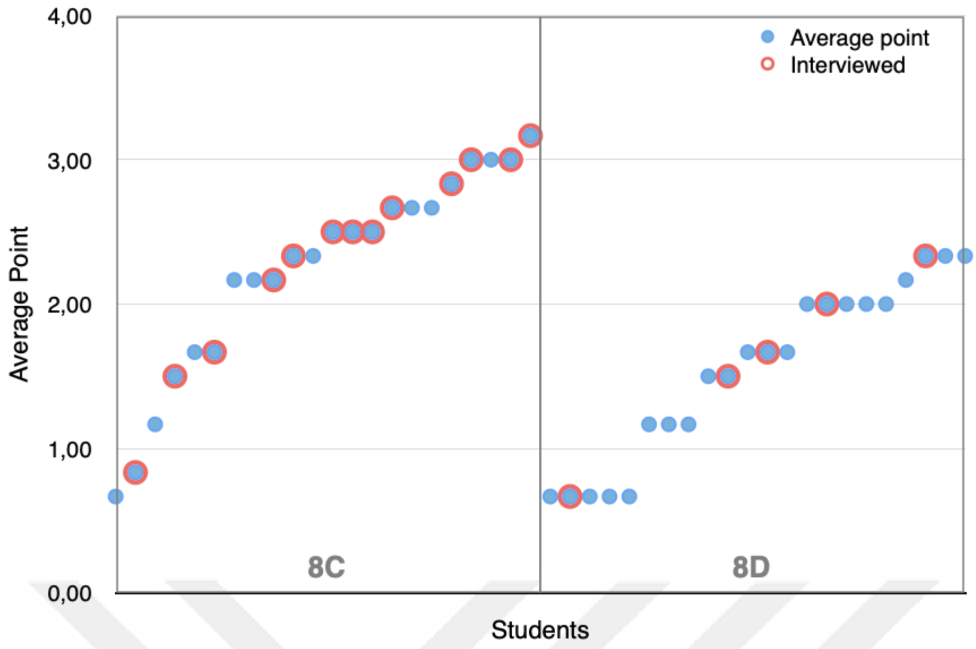

Figure 18. Students interviewed.

The rates and percentages of correct answers for the scientific achievement test questions are presented in detail below.

Furthermore, in the analysis of the scientific achievement test using the SOLO Taxonomy, the scores of students who made computational errors in the questions or showed simple inattention when reading graphs were not affected. The table below shows the error rates of the students (Figure 19).

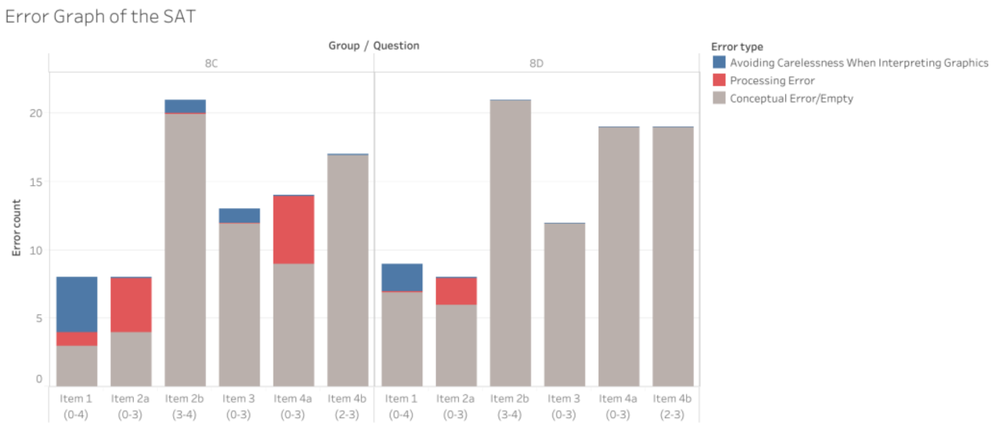

Figure 19. Error graph of the SAT.

4.2.1 Question 1. The outcomes of the first question on the scientific achievement test are as follows:

"M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation.

"M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships".

This question assesses the ability to interpret two different graphs with varying data and identify the correlation between them.

Table 11 shows the answer percentages of the question based on the SOLO Taxonomy steps.

Table 11

Percentage of Answered Questions for Question 1

		No Score	Unistructural (1 point) %	Multistructural (2 point) %	Relational (3 point) %	Extended Abstract (4 point) %
Item 1	Experimental Group	%0	%0.05	%4.54	%9.09	%77.27
	Control Group	%9.09	%18.18	%0	%13.63	%59.09

After analyzing the responses to the first question, it was found that 77.27% of students in the experimental group and 59.09% of students in the control group answered in the 'Extended Abstract' category. The experimental group had a higher percentage of responses at the extended abstract level than the control group, and there were no students at the 'No Score' level in the experimental group, while the percentage of students at the 'Unistructural' level was very low.

4.2.2 Question 2. The scientific achievement test's second question comprises two items. The outcomes of the second question's item "a" are as follows:

“M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation.

M.8.2.2.5. Creates and interprets equations, tables, and graphs of real life situations with linear relationships.”

In this question, the skill of expressing the heights of balloons changing over time on a graph with a linear equation is measured.

The outcome of the second question's item “b” are as follows:

M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.

For this task, students are required to interpret the balloons on the same graph in relation to each other and determine a general term based on the difference between them.

Table 12 shows the answer percentages of the question based on the SOLO Taxonomy steps.

Table 12

Percentage of Answered Questions for Question 2

		No Score	Unistructural (1 point) %	Multistructural (2 point) %	Relational (3 point) %	Extended Abstract (4 point) %
Item 2a	Experimental Group	%9.09	%9.09	%0	%81.81	
	Control Group	%13.63	%0	%13.63	%72.72	
Item 2b	Experimental Group	%36.36	%4.54	%0	%50	%9.09
	Control Group	%77.27	%0	%0	%18.18	%4.54

In relation to question 2a, both groups had the highest rate of answering the question in the 'Extended Abstract' category. Additionally, the presence of the 'No Score' category in both groups indicates that there were participants who were unable to answer the question or express their answer correctly.

In relation to question 2b, the experimental group demonstrated a higher cognitive level than the control group, as evidenced by their higher percentages in the 'Relational' and 'Extended Abstract' categories and lower percentages in the 'No Score' and 'Unistructural' categories. The researcher added this item to measure the high cognitive level steps of the SOLO Taxonomy. The highest category in the control group is 'no score', while in the experimental group, it is the second-highest category. Moreover, the percentage of answers in the 'multistructural' and 'extended abstract' categories in the experimental group was more than half of the percentage of answers in the same categories in the control group.

4.2.3 Question 3. The outcomes of the third question on the scientific achievement test are as follows:

“M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships.”

In this question, the student is expected to read the time when the change in money spent and the change in money remaining over time are equalized on the graph.

Table 13 shows the answer percentages of the question based on the SOLO Taxonomy steps.

Table 13

Percentage of Answered Questions for Question 3

		No Score	Unistructural (1 point) %	Multistructural (2 point) %	Relational (3 point) %
Item 3	Experimental Group	%13.63	%9.09	%36.36	%40.90
	Control Group	%36.36	%4.54	%13.63	%45.45

Both groups answered the question in the 'Relational' category at the highest rate. The control group scored higher than the experimental group in the 'Relational' step. However, the experimental group scored higher than the control group in the total scores for the 'Multistructural' and 'Relational' steps. It is worth noting that some students in both groups were unable to answer the question correctly. The experimental group had a three-fold advantage in the number of students who answered the question correctly.

4.2.4 Question 4. The scientific achievement test's fourth question comprises two items. The outcomes of the fourth question's item "a" are as follows:

"M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation.

M.8.2.2.5. Creates and interprets equations, tables and graphs of real life situations with linear relationships."

This question requires the reader to interpret a graph displaying the toner levels and number of shots for two photocopiers. The question assesses the ability to follow multiple processes and establish relationships between variables. Additionally, the reader must calculate fees by establishing a proportion with the given information.

The outcome of the fourth question's item "b" are as follows:

M.8.2.2.3. Expresses how one of the two variables, which have a linear relationship between them, changes depending on the other, with a table and an equation.

Using the provided information, it is necessary to compare the two machines and select the preferred option based on the given criteria.

Table 14 shows the answer percentages of the question based on the SOLO Taxonomy steps.

Table 14

Percentage of Answered Questions for Question 4

		No Score	Unistructural (1 point) %	Multistructural (2 point) %	Relational (3 point) %
Item 4a	Experimental Group	%18.18	%4.54	%18.18	%59.09
	Control Group	%45.45	%36.36	%4.54	%13.63
Item 4b	Experimental Group	%54.55	%0	%22.73	%22.73
	Control Group	%77.27	%0	%9.09	%13.63

The comprehension level of the experimental group was higher than that of the control group. This is supported by the higher percentages of the experimental group in the 'Multistructural' and 'Relational' categories, and the lower percentages in the 'No Score' and 'Unistructural' categories.

Additionally, in item a of the 4th question, the experimental group had a 4-fold ratio advantage over the control group in the 'relational' step.

Item b of the question is a challenging task in the test. The researcher included this item to assess the higher cognitive level steps of the SOLO Taxonomy. The step with the highest percentage in both groups was the 'No Score' step. Additionally, the experimental group had a sum percentage of 'Multistructural' and 'Relational' steps close to 50%, while the control group had only about half of this value.

4.3 The Results of the Post-Scientific Achievement Test

To answer the first research question, “Is there a significant difference in the mathematical achievement scores related to linear equations, which are part of the algebra unit, between the experimental group and the control group students after the experimental process?” an independent t-test between the two groups was applied in the SPSS program.

4.3.1 Test of normality of the post-SAT. Tables 15 display the distribution of scientific achievement test averages for the experimental and control groups.

Table 15

The Results of Shapiro-Wilk Test and Skewness/Kurtosis Values for the Post-SAT

		Shapiro-Wilk			Descriptives	
		Statistic	df	Sig.	Skewness	Kurtosis
Average score	Experimental group	0.19	22	0.06	0.87	-0.02
	Control group	0.18	22	0.02	-0.33	-1.29

The Shapiro-Wilk test yielded significant values of 0.06 and 0.02. The data exhibited a normal distribution. It is recommended to examine the 'Skewness and Kurtosis' values, which should ideally fall within the range of -2 to 2.

4.3.2 Independent samples t-test for the post-SAT. To answer the research question of the study, an independent samples t-test was conducted to determine if there was a significant difference in mathematical achievement scores related to linear equations, which are part of the algebra unit, between the experimental group and the control group students after the experimental process. Table 16 contains the results of the post scientific achievement test.

Table 16

Independent Samples T - Test for the Post-SAT

	Levene's Test		t-test			Confidence interval	
	F	Sig.	t	df	Sig.	Lower	Upper
Equal variances assume	0.17	0.69	3.48	42	0.001	1.74	6.54
Equal variances not assumed				40.94	0.001	1.73	6.54

An independent samples t-test was conducted to compare the average scores of the experimental group (*M* = 13.41, *SD* = 4.25) and the control group (*M* = 9.27, *SD* = 3.61). The t-test revealed a statistically significant difference between the groups ($t(42) = 3.48$, $p = 0.001$). The effect size, as measured by Cohen's d (1988), was d = 0.21, indicating a medium effect.

Additionally, Levene's Test for equality of variances was run before interpreting the results of t testing. Because the significance value was greater than .05 in Levene's Test (.69), equal variances were assumed.

4.4 Descriptives Statistics of the Systems Dynamics Comprehension Test

The System Dynamics Comprehension Test was administered only to the experimental group students as a posttest. It consisted of six questions, including two multiple-choice questions, one fill-in-the-blank question, one question requiring the drawing of a graph and writing an equation, and one question requiring the completion of a stock-flow diagram. The final question was open-ended and asked for the students' evaluation of the mathematics lessons taught with system dynamics. The initial five questions of the system dynamics comprehension test were assessed using the same SOLO Taxonomy steps as the scientific achievement test. The evaluation range and percentage of students who answered each question are provided below.

Upon analyzing the answer percentages of the students, it is evident that all students answered items 1 and 2 correctly. These items pertain to the concepts of stock, flow, and behavior graph over time, and it is apparent that all students have a basic understanding of these fundamental concepts.

Table 17

Percentage of Answered Questions for the SDT

	No Score	Unistructural (1 point) %	Multistructural (2 point) %	Relational (3 point) %	Extended Abstract (4 point) %
Item 1	%0	%0	%100		
Item 2	%0			%100	
Item 3	%0			%36.36	%63.63
Item 4	%0		%36.36	%63.63	
Item 5	%0		%100	%0	

Question 3 required students to draw a stock-flow diagram of a given problem situation, construct a graph of behavior over time, and write the equation of the graph. Many students struggled with writing the equation, leading to mistakes in their answers.

For Question 4, which required them to fill in the blanks for inflow, stock, and outflow flows. Specifically, students had difficulty understanding how inflows and output flows affected the stock, with many making errors related to the output flow. This same issue was also observed in Question 5, where students were asked to place factors in a problem situation using a stock-flow diagram. Most students were unable to correctly identify all the factors. Many assumed that factors leading to a decrease in stock would be listed in the inflow for positive events and in the outflow for negative events.

4.5 Correlations between Systems Dynamics Comprehension and Scientific Achievement Test

To determine whether there is a correlation between the experimental group students' scientific achievement test results and their system dynamics comprehension test results, a correlation test was conducted using the SPSS program. Table 18 and Table 19 provide descriptive statistics and correlation scores for the two tests.

Table 18

Descriptive Statistics for the SDT and SAT for Experimental Group

	Mean	Sd.	N
Total Score SDT	13.27	0.70	22
Total Score SAT (experimental group)	13.41	4.25	22

The System Dynamics Comprehension Test consists of 5 items (*M* = 13.27, *SD* = 0.70). The Scientific Achievement Test has 6 items with question choices (*M* = 13.41, *SD* = 4.25).

Table 19

Correlation Between SDT and SAT Scores

	SDT score	SAT score
SDT score	1	0.57
SAT score	0.57	1

Table 19 shows a moderate correlation (r = 0.57) between the Total Score SDT and Total Score SAT of the experimental group. This suggests that participants in the experimental group with high Total Score SDT also tend to have high Total Score SAT, indicating a statistically significant relationship between the two measures.

4.6 Students' Attitudes Towards Linear Equations

This question was answered by only the students in the experimental group, which consisted of 22 individuals. To answer the research question, 'How does teaching mathematics using the System Dynamics approach affect eighth-grade students' attitudes towards linear equations?'. The following are the students' responses to the 6th question of the System Dynamics Comprehension Test.

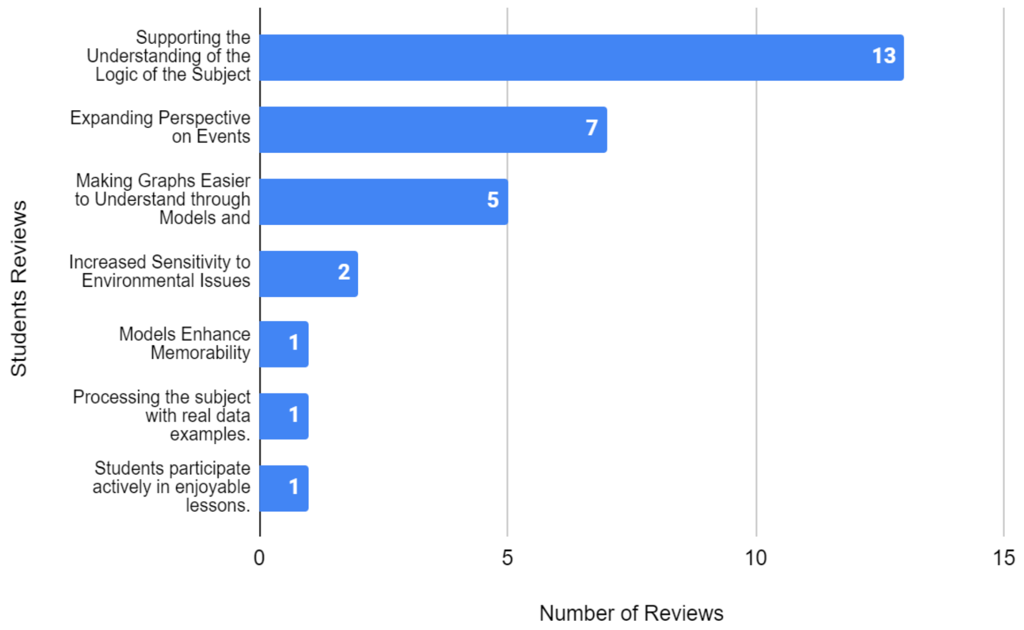

Figure 20. Students reviews for SDT.

Upon examination of the figure, it is evident that over 50% of the students noted that the most significant aspect of the mathematics lesson process utilizing system dynamics was its ability to aid in their comprehension of the subject's logic. Seven students expressed that the systems thinking approach expanded their perspectives, while five students stated that the modeling of linear graphs in the STELLA Online application helped them to better understand the graphs and solidify their understanding of the subject. In addition, 2 students stated that their environmental sensitivity increased when the topic of linear equations was taught around environmental problems. Drawing graphs with real data, models increasing memorability and student-centered lessons are also comments made by one student.

Chapter 5

Discussion and Conclusions

The purpose of this study was to investigate the effect of system dynamics tools on students' achievement, understanding of system dynamics, and attitudes toward the linear equations course in mathematics This section will discuss the results of scientific achievement tests (SAT), the correlation between the results of the system dynamics comprehension test (SDT) and the results of the scientific achievement test, and students' attitudes towards the teaching of linear equations with system dynamics tools and suggestions for future studies are made.

The scientific achievement post-test results indicate that the control group achieved a score of 9.27, while the experimental group achieved a score of 13.41. A statistically significant difference was observed between the two groups. These findings suggest that the use of system dynamics tools in the mathematics course, specifically in the subject of linear equations, has an impact on students' mathematics achievement. This suggests that integrating system dynamics tools into the mathematics course, specifically in the subject of linear equations, can enhance student achievement.

The relationship between a linear equation and its corresponding linear graph is often a challenging concept to grasp. Many students encounter difficulties in comprehending linear equations due to a lack of conceptual understanding, inability to relate concepts, and difficulty in applying concepts to solve problems. System dynamics tools are employed to elucidate relationships between phenomena through numerical models created by students. The behavior of the models over time is plotted to facilitate the interpretation of the linear relationship. In the final question of the Systems Dynamics Comprehension Test, the experimental group was asked to evaluate the effectiveness of teaching mathematics with systems dynamics tools. Over 50% of the students indicated that the tools assisted them in comprehending the subject matter, while over 25% of the students reported that the systems thinking approach broadened their perspectives. Additionally, over 20% of the students found linear graphs more comprehensible through the models. The findings indicate that system dynamics tools can assist students in comprehending linear equations. Furthermore, the integration of system dynamics tools in linear equations has the potential to enhance students' attitudes towards mathematics courses. Additionally, the study aimed to enhance students' capacity to interpret and comprehend causal relationships between variables through the use of models, as well as to facilitate their ability to predict the behavior of events over time and draw conclusions. It was observed that these objectives were successfully achieved. Another objective of the study is to enhance students' awareness and sense of responsibility towards the environment by integrating authentic environmental issues into the curriculum. In the final question of the system dynamics comprehension test, two students indicated that the incorporation of real-world environmental problems was an effective method for heightening their sensitivity to environmental concerns. The integration of such examples into each academic discipline has the potential to enhance the awareness of a broader range of students.

The results of the system dynamics comprehension test indicated that a significant proportion of the questions required the students to demonstrate their understanding of the graphs of stock, flow, and behavior, which change over time, and to establish relationships between models and graphs. This suggests that one of the objectives of the study, which was to enable students to understand the systems thinking approach and to establish the relationships between the basic tools of system dynamics such as stock-flow and the behavior graphs of factors over time, was achieved.

A moderate correlation ($r = 0.57$) was observed between the results of the system dynamics comprehension test and the scientific achievement test administered to the experimental group. This relationship suggests that the use of system dynamics tools may influence mathematics achievement, or that students who perform well have a more comprehensive understanding of system dynamics tools (Figure 21).

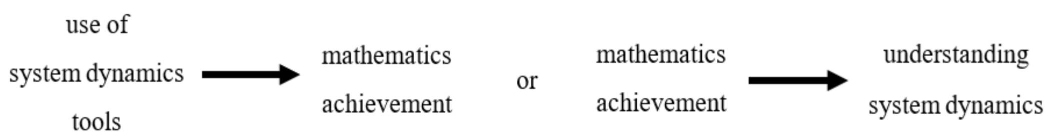

Figure 21. Correlation between system dynamics tools and mathematics achievement.

Grant (1998) supports the research results and states that the systems thinking approach provides a “common conceptual framework and vocabulary” for interdisciplinary education programmes (p. 70). These findings are in line with previous research. A study conducted by Amida, Hung, and Algarni (2023) highlighted that students demonstrated the greatest improvement in their understanding of the concepts of interconnection, linearity, and wholeness. The research findings indicate that modeling with systems thinking can assist students in identifying inconsistencies between given and targeted problem situations. Additionally, Nguyen and Santagata (2021) found that using the systems thinking approach improves students' ability to provide consistent cause-and-effect statements when explaining their ideas and evidence. Salado, Chowdhury, and Norton (2019) also reported a positive impact of the systems thinking approach on problem-solving skills.

Four of the six questions in the scientific achievement test were derived from the sample questions published by the Ministry of National Education. The remaining two questions were included by the researcher as additional options for two of these questions. In both groups of the study, the two items that measured high-level learning skills according to the SOLO Taxonomy and were added to the scientific achievement test by the researcher were the questions that were least correctly answered by the students. The reason for this result is that these items are challenging and require advanced cognitive abilities. The problem identification part of the study emphasized the difference between higher and lower thinking skills, which was also evident in the test results. Students found it difficult to cope with questions that required the application of basic concepts, rules, and formulas, but they also had difficulty with questions that required more advanced cognitive skills such as abstraction, generalization, and thinking about multiple relationships. This indicates that the utilization of system dynamics tools facilitates the development of higher-order thinking abilities, as evidenced by the superior performance of the experimental group students in comparison to the control group students. Upon analysis of the test results, which include the two items added by the researcher and identified as challenging and discriminating questions, it becomes evident that the skills-oriented tests lack the necessary discriminatory capacity to accurately assess higher-order thinking abilities.

The mathematics curriculum in Turkey aims to develop higher order thinking skills, such as problem-solving, knowledge transfer, and interdisciplinary and critical thinking skills, referred to as 21st-century skills. However, the current curriculum content and assessments are inadequate in achieving this goal (Gelen, 2017) (depicted as A in Figure 22). A systems thinking approach and system dynamics tools can be recommended to develop students' higher-order thinking skills (depicted as B in Figure 22). This can help bridge the gap between the current and desired curriculum.

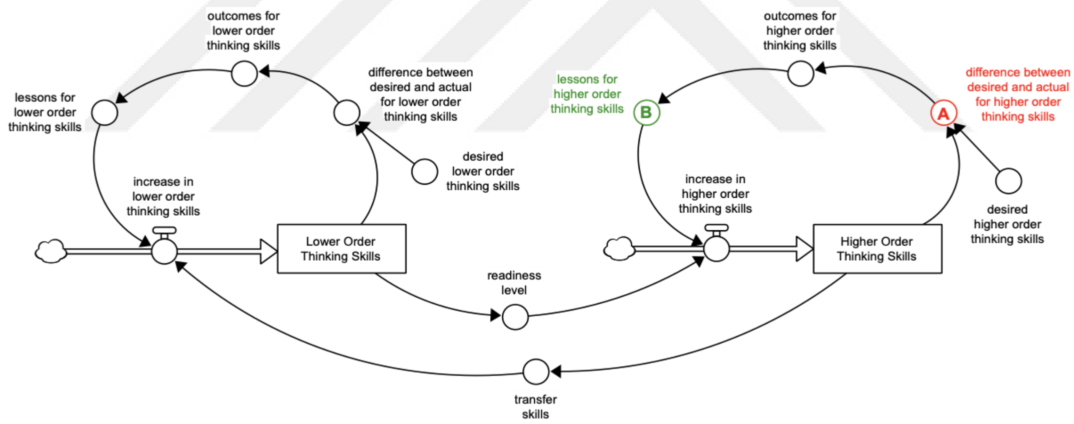

Figure 22. Mathematics competencies desired situation with research results and intervention.

When the lesson plans created and implemented with system dynamics tools are analyzed, it was observed that the use of such tools had a more positive impact on long-term achievement (Karaarslan, Semiz & Teksöz, 2024). Because systems thinking is a way of thinking about a problem, it requires time to be fully understood (Fisher, 2016). The more students are exposed to lesson plans prepared with a systems thinking approach, the more easily they can think in systems. It is possible to become a systems thinker by engaging more with systems thinking. It is a habit to think systematically (Sistem Düşüncesi Derneği, 2021). Initially, finding the most appropriate solution for a problem may be challenging. However, as you define the problem better and experiment with the solution, the habit of thinking systematically develops. Each trial is a step towards achieving the desired result. As this habit is acquired, students progress towards becoming system thinkers. Richmond (1994) defined systems thinking as the understanding of the underlying structure in depth over time and drawing reliable conclusions about behavior. Forrester (2009) highlights that the use of these tools, from kindergarten to university level, empowers students to modify their own cognitive processes. Based on all this, the education system should increase the use of the systems thinking approach in order to expose students to this way of thinking.

If Stella Online is considered within the framework of technological tools, the implementation of technology-supported projects often necessitates the formation of student groups, which facilitates the development of students' collaboration and communication skills. Students are able to share models, discuss results, and solve problems collectively. This collaborative environment is analogous to many modern workplaces and is therefore conducive to the preparation of students for future careers where teamwork and technology are essential (Dillenbourg, Järvelä & Fischer, 2009).

Technologies such as Stella Online are appropriate tools to create this environment. The use of Stella Online transforms traditional mathematics lessons into interactive sessions where students can actively engage with the material. Students can manipulate models, run simulations, and see the results of their changes immediately (Sokolowski & Banks, 2011). This hands-on approach can increase student engagement and motivation, and at the same time make mathematics lessons more attractive and less intimidating. Furthermore, lessons can be tailored to accommodate the diverse needs of students. Educators can develop models that vary in complexity to provide suitable challenges for varying skill levels. Students can work at their own pace, explore models that align with their interests or align with their current level of understanding, and personalize their learning experience (Tomlinson, 2001).

Moreover, online applications such as Stella Online can be accessed from any location with an internet connection, thereby affording students greater flexibility in terms of the manner and location of their learning. This is particularly advantageous in distance or hybrid learning environments (Means et al., 2009). Furthermore, the incorporation of technology into homework assignments or independent study projects allows for the extension of learning beyond the classroom.

In conclusion, integrating Stella Online into mathematics lessons transforms the use of technology from a supplementary tool to a central component of the learning process. It enhances visualization, promotes interactivity, demonstrates real-world applications, develops critical skills, supports differentiated instruction, encourages collaboration, and offers flexibility. These changes not only enhance the accessibility and engagement of mathematics for students, but also better prepare them for a future in which technology will play an increasingly prominent role (De Jong, Linn, & Zacharia, 2013).

5.1 Recommendations

This study implemented lesson plans that focused on the acquisition of linear equations using system dynamics tools. Regular exposure to system dynamics and time spent with these tools are necessary to become a systems thinker. The lesson plan was effective in understanding the subject matter and increasing students' achievement. However, to be more effective in the long run, it is recommended that system dynamics tools be implemented simultaneously in all disciplines. A careful selection of subjects for the application of system dynamics tools, along with longer lesson hours, can further enhance their effectiveness. The study also revealed some misconceptions: that outflows always decrease the stock value and inflows always increase the stock value. These misconceptions can be eliminated in long term applications. Additionally, if the Ministry of National Education increases the content aimed at developing high-level thinking skills, the impact of these tools will be even more pronounced in such courses. The recently published curriculum introduces a systems thinking approach, which focuses on developing and assessing various types of literacy skills. This could be a promising starting point (MoNE, 2024).

To integrate system dynamics tools into various disciplines, teachers require support through in-service training on the systems thinking approach and system dynamics tools. The Ministry of National Education and school administrations have a significant role to play in this regard. In addition to the substantive material, the integration of inquiries and evaluative instruments designed to gauge high-order cognitive abilities stands as a pivotal stride in fostering skill development.

One of the objectives of this study is to present examples of mathematics lesson plans created using the system dynamics approach as a model for mathematics teachers and pre-service teachers. The aim is to encourage the wider use of the system dynamics approach in education. This study can serve as a model for pre-service teachers and teachers in mathematics or science courses.

REFERENCES

Ackoff, Russell L., with Herbert J. Addison and Andrew Carey, Systems Thinking for Curious Managers, Triarchy Press Limited, Axminster, UK, 2010.

Adis, C., Wisecarver, M., Raber, C., Wind, A. P., Canali, K. G., & Personnel Decisions Research Inst (Pdri) Inc Tampa Fl Tampa United States. (2017). Innovative tools to assess systems thinking ability. *US Army Research Institute for the Behavioral and Social Sciences*.

Altıner, E. Ç. (2021). Gerçekçi matematik eğitimi üzerine bir kuramsal çalışma. *Eğitim ve Teknoloji*, *3*(1), 48-73.

Amida, A., Hung, W., & Algarni, S. (2023). System modelling: Exploring engineering students perceptions and learning outcomes. *Systems Research and Behavioral Science.* doi: 10.1002/sres.2996

Anderson, V., & Johnson, L. (1997). *Systems thinking basics* (pp. 1-14). Cambridge, MA: Pegasus Communications.

Ari, M. E. (2022). *8. Sınıf Matematik Ders Kitabındaki Etkinlik ve Klçme Değerlendirme Sorularının incelenerek lgs Sınav Soruları ile Karşılaştırılması ve Öğretmen Görüşlerinin Alınması* (PhD dissertation). Retrieved from https://openaccess.marmara.edu.tr/entities/publication/9bbe0a07-a80e-4294-ba20-a59376700bc8

Arnold, R. D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. *Procedia computer science*, *44*, 669-678.,

Arslan, M. (2007). Constructivist approaches in education. *Ankara University Journal of Faculty of Educational Sciences (JFES)*, *40*(1), 41-61.

Assaraf, O. B. Z., & Orion, N. (2010). System thinking skills at the elementary school level. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *47*(5), 540-563.

Aşık, G., & Doğança Küçük, Z. (2021). Metacognition in action as a possible explanation for stock-flow failure. *System Dynamics Review*, *37*(4), 253-282.

Atmaca, E. (2019). *Improving Tenth Graders' Understanding of Global Carbon Cycle: A Systems Learning Approach* (PhD dissertation, Boğaziçi University). Retrieved from https://drive.google.com/file/d/1nNTGtSYwehlFlp72zj_fCtmHYBj2UoVT/view?pli=1

Aydın, N., & Yılmaz, A. (2010). Yapılandırıcı yaklaşımın öğrencilerin üst düzey bilişsel becerilerine etkisi. *Hacettepe Üniversitesi Eğitim Fakültesi Dergisi*, *39*(39), 57-68.

Barlas, Y. (2007). System dynamics: systemic feedback modeling for policy analysis. *System*, *1*(59), 1-68.

Biggs, J. B., & Collis, K. F. (1982). The psychological structure of creative writing. *Australian Journal of Education*, *26*(1), 59-70.

Biggs, J., & Collis, K. (1989). Towards a model of school-based curriculum development and assessment using the SOLO taxonomy. *Australian journal of education*, *33*(2), 151-163.

Biggs, J., & Tang, C. (2011). *Teaching For Quality Learning At University*. (4th ed.). McGraw-hill education (UK).

Biggs, J., Tang, C., & Kennedy, G. (2022). *Ebook: Teaching for Quality Learning at University 5e*. McGraw-hill education (UK).

Bishop, A. (1991). *Mathematical enculturation: A cultural perspective on mathematics education* (Vol. 6). Springer Science & Business Media.

Blatti, J. L., Garcia, J., Cave, D., Monge, F., Cuccinello, A., Portillo, J., ... & Schwebel, F. (2019). Systems thinking in science education and outreach toward a sustainable future. *Journal of chemical education*, *96*(12), 2852-2862.

Bloom, B. S. (1956). *Taxonomy of educational objectives, the classification of educational goals, handbook I: Cognitive domain.* New York: David McKay Company.

Bulut, A. (2022). Analysis of the Problems of the Turkish Education System in Terms of the Elements of Educational Programs. *International Society for Technology, Education, and Science*.

Calamlam, J. M. M., Ocampo, R. V., & Reyes, Z. Q. (2015). Understanding of students on linear equations through analysis of self-made questions. *International Journal of Technical Research and Applications [Special Issue], 22*, 117-130.

Capra, F., & Luisi, P. L. (2014). *The systems view of life: A unifying vision*. Cambridge University Press.

Creating Learning Exchange. (1991). *About The Creative Learning Exchange*.Retrieved April 9, 2024 from http://www.clexchange.org/cle/about.asp

Çelikten, A. (2022). *Türk Dili ve Edebiyatı dersinde eğitimde sistem düşüncesi araçlarının kullanılmasının eser analizinde derin okumaya etkisi* (Yayımlanmamış yüksek lisans tezi). Maltepe Üniversitesi, İstanbul, Türkiye.

De Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science*, *340*(6130), 305-308.

Demir, Ş. (2016). Stok Akış Diyagramları ile Problem Çözüyoruz. *Eğitimde Sistem Düşüncesi Yıllığı, (3).*

Dillenbourg, P., Järvelä, S., & Fischer, F. (2009). *The evolution of research on computer-supported collaborative learning: From design to orchestration* (pp. 3-19). Springer Netherlands.

Doganca Kucuk, Z., & Saysel, A. K. (2018). Developing seventh grade students' understanding of complex environmental problems with systems tools and representations: a quasi-experimental study. *Research in Science Education*, *48*, 491-514.

Doganca, Z., & Saysel, A. K. (2012). An Interview Protocol for Assessing Students' Understanding of Dynamically Complex Environmental Problems. *The Project, Institute of Environmental Sciences, Bogazici University*.

Doğança, Z. (2013). Designing System Based Environmental Instruction Program and Evaluating İts Effects on Seventh Grade Students. *Unpublished PhD Dissertation, Bogazici University, Istanbul*.

Eğitimde Sistem Düşüncesi Derneği. (2023). Eğitimde Sistem Düşüncesi Türkiye K-4 Deneyimi. *Eğitimde Sistem Düşüncesi Yıllığı, (10).*

Eğitimde Sistem Düşüncesi, (2016), *Sistem Düşüncesi Tanımlar*. Retrieved December 14, 2023, from https://egitimdesistemdusuncesi.org/nedir/tanimlar.php

Ehrlinger, J., & Eibach, R. P. (2011). Focalism and the failure to foresee unintended consequences. *Basic and Applied Social Psychology*, *33*(1), 59-68.

Elm, J. M., Goldenson, D. R. (2012*). The business case for systems engineering study: results of the systems engineering effectiveness survey*. Carnegie Mellon University, Software Engineering Institute [Report No. CMU/SEI-2012-SR-009].

Elmas, R., Arslan, H. Ö., Pamuk, S., Peşman, H., & Sözbilir, M. (2021). Systems Thinking Approach in Science Education. *Journal of the Turkish Chemical Society, Section C: Chemical Education*, *6*(1), 107-132.

English, L. D. (2012). Data modelling with first-grade students. *Educational Studies in Mathematics*, *81*, 15-30.

Ericsson, K. A. & Herbert A. S. (1993). Protocol Analysis: Verbal Reports as Data. Cambridge, MA: MIT.

Fannakhosrow, M., Nourabadi, S., Ngoc Huy, D. T., Dinh Trung, N., & Tashtoush, M. A. (2022). A Comparative Study of Information and Communication Technology (ICT)-Based and Conventional Methods of Instruction on Learners' Academic Enthusiasm for L2 Learning. *Education Research International*, *2022*(1), 5478088. doi: 10.1155/2022/5478088

Feriver, Ş. (2022). Pre-schoolers as systems thinkers: testing the water. *Environmental Education Research*, *28*(3), 430-456.

Ferrini-Mundy, J. (2000). Principles and standards for school mathematics: A guide for mathematicians. *Notices of the American Mathematical Society*, *47*(8).

Fisher, D. M. (2005). *Modeling dynamic systems: lessons for a first course. Teachers and trainer's guide* (No. 003 F533m). Diana M. Fisher.

Fisher, D. M. (2018). Reflections on teaching system dynamics modeling to secondary school students for over 20 years. *Systems*, *6*(2), 12.

Fisher, D. M., & Göktepe, E. (2021). Creating assessment questions for systems thinking concepts. In *Proceedings from the International System Dynamics Conference. Chicago, IL*.

Fisher, D. M., & Systems Thinking Association. (2023, February). Systems thinking activities used in K-12 for up to two decades. In *Frontiers in Education* (Vol. 8, p. 1059733). Frontiers.

Fisher. D. O. (2001). *Lesson in Mathematics: A Dynamic Approach*. Lebanon NH: Isee Systems.

Ford, D. N. (2019). A system dynamics glossary. *System dynamics review*, *35*(4), 369-379.

Forrester, J. (2009). Learning through system dynamics as preparation for the 21st century. *Paper presented at the K-12 Systems Thinking and Dynamic Modeling Conference*, Wellesley, MA.

Forrester, J. W. (1968). Principles of systems. Wright-Allen Press.

Forrester, J. W. (1992). System dynamics and learner-centered-learning in kindergarten through 12th grade education. *Text of remarks delivered December 12,* 1992.

Forrester, J. W. (1994, June). Learning through system dynamics as preparation for the 21st century. Keynote *address for systems thinking and dynamic modeling conference for K-12 Education* (pp. 27-29). Concord Academy Concord, MA.

Forrester, J. W. (1995). The beginning of system dynamics. *McKinsey Quarterly*, 4-17.

Forrester, J. W. (2009). Some basic concepts in system dynamics. *Sloan School of Management*, 1-17.

Frank, M. (2010). Assessing the interest for systems engineering positions and other engineering positions' required capacity for engineering systems thinking (CEST). *Systems Engineering*, *13*(2), 161-174.

Frank, M., Frank, M., Shaked, H., & Koral-Kordova, S. (2016). *Systems thinking: Foundation, uses and challenges*. Nova Science Publishers, Inc.

Frodeman, R., Klein, J. T., & Pacheco, R. C. D. S. (Eds.). (2017). *The Oxford handbook of interdisciplinarity* (s. 292). Oxford University Press.

Gelen, İ. (2017). P21-Program ve öğretimde 21. yüzyıl beceri çerçeveleri (ABD Uygulamaları). *Disiplinlerarası Eğitim Araştırmaları Dergisi*, *1*(2), 15-29.

Ginzburg, T., & Barak, M. (2023). Technology-Enhanced Learning and Its Association with Motivation to Learn Science from a Cross-Cultural Perspective. *Journal of Science Education and Technology*, 1-10.

Göktepe, E. (2022). *Eğitimde Sistem Düşüncesi.* Ankara, Türkiye : Koza Yayın Dağıtım.

Grant, W. E. (1998). Ecology and natural resource management: reflections from a systems perspective. *Ecological Modelling*, *108*(1-3), 67-76.

Hasibuan, S. A., & Fauzi, K. M. A. (2019). Development of PISA mathematical problem model on the content of change and relationship to measure students mathematical problem-solving ability. *International Electronic Journal of Mathematics Education*, *15*(2), em0570. doi : 10.29333/iejme/6274

Hubbard, J. H., & West, B. H. (1997). *Differential equations: A dynamical systems approach: Ordinary differential equations* (Vol. 5). Springer Science & Business Media.

Ilhan, M., & Guler, N. (2018). A comparison of difficulty indices calculated for open-ended items according to classical test theory and many facet rasch model. *Eurasian journal of educational Research*, *18*(75), 99-114.

İlhan, M., & Gezer, M. (2017). A comparison of the reliability of the Solo-and revised Bloom's Taxonomy-based classifications in the analysis of the cognitive levels of assessment questions. *Pegem Egitim Ve Ogretim Dergisi= Pegem Journal of Education and Instruction, 7*(4), 637.

Karaarslan Semiz, G., & Teksöz, G. (2020). Developing the systems thinking skills of pre-service science teachers through an outdoor ESD course. *Journal of Adventure Education and Outdoor Learning, 20*(4), 337-356.

Karaarslan Semiz, G., & Teksöz, G. (2024). Tracing system thinking skills in science curricula: A case study from Turkey. *International Journal of Science and Mathematics Education, 22*(3), 515-536.

Kaya, N., Ellez, A. M., & Ellez, N. (2019). The effect of system thinking approach on the environmental consciousness of pre-school children. *Route Educational and Social Science Journal, 6*(5), 36-50.

Kim, D. H. (1999). *Introduction to systems thinking* (Vol. 16). Waltham, MA: Pegasus Communications.

Klassen, A. C., Creswell, J., Plano Clark, V. L., Smith, K. C., & Meissner, H. I. (2012). Best practices in mixed methods for quality of life research. *Quality of life Research, 21*, 377-380.

Korkmaz, S., Dündar, S., & Yaman, H. (2016). Problem çözmede zihnin matematiksel alışkanlıkları. *Turkish Journal of Computer and Mathematics Education (TURCOMAT), 7*(1), 35-61.

Krantz, S. G. (2010). *An episodic history of mathematics: Mathematical culture through problem solving* (Vol. 19). Maa.

Küçükoğlu, A., Nuhoğlu, H., & Taşçı, A. D. (2023). Sistem düşüncesi ile ilgili yapılan eğitim araştırmalarının bibliyometrik analizi. *E-International Journal of Educational Research, 14*(4), 126-145.

Lopes, C. E., Grando, R. C., & D’Ambrosio, B. S. (2017). Experiences situating mathematical problem solving at the core of early childhood classrooms. *Early Childhood Education Journal, 45*, 251-259.

Maani, K. E., & Maharaj, V. (2001, July). Systemic Thinking and Complex Problem Solving. A Theory Building Empirical Study. In *Proceedings of the 19 th International Conference of the System Dynamics Society 2001* (p. 101).

Maani, K. E., & Maharaj, V. (2004). Links between systems thinking and complex decision making. *System Dynamics Review: The Journal of the System Dynamics Society*, *20*(1), 21-48.

Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing.

Michener, E. R. (1978). Understanding understanding mathematics. *Cognitive science*, *2*(4), 361-383.

Milli Eğitim Bakanlığı. (2024). *Türkiye Yüzyılı Maarif Modeli.*.Retrieved June 5, 2024 from https://mufredat.meb.gov.tr/

Milli Eğitim Bakanlığı. (2019). *PISA 2018 Türkiye Ön Raporu.*Retrieved October 23, 2023 from https://pisa.meb.gov.tr/meb_iys_dosyalar/2023_05/15170226_PISA_2018_Turkiye_On_Raporu.pdf

Milli Eğitim Bakanlığı. (2022). *8. Sınıf Matematik Ünitelendirilmiş Örnek Sorular 2022*. Retrieved January 23, 2024 from https://cdn.eba.gov.tr/yardimcikaynaklar/2022/11/kt/8kt/mat/4.pdf

Milli Eğitim Bakanlığı. (2022). *Liselere Geçiş Sistemi Raporu 2022.*Retrieved October 23, 2023 from https://cdn.eba.gov.tr/icerik/2022/06/2022_LGS_rapor.pdf

Milli Eğitim Bakanlığı. (2023). *Liselere Geçiş Sistemi.* Retrieved October 23, 2023 from https://odsgm.meb.gov.tr/www/liselere-gecis-sistemi/icerik/1012

Milli Eğitim Bakanlığı. (2023). *PISA 2022 Türkiye Raporu.*Retrieved December 13, 2023 from https://pisa.meb.gov.tr/meb_iys_dosyalar/2023_12/05125555_pisa2022_rapor_051223.pdf

Monat, J. P., & Gannon, T. F. (2015). What is systems thinking? A review of selected literature plus recommendations. *American Journal of Systems Science*, *4*(1), 11-26.

Mulbar, U., Rahman, A., & Ahmar, A. (2017). Analysis of the ability in mathematical problem-solving based on SOLO taxonomy and cognitive style. *World Transactions on Engineering and Technology Education*, *15*(1), 68-73.

Nagarajan, S., & Overton, T. (2019). Promoting systems thinking using project-and problem-based learning. *Journal of Chemical Education*, *96*(12), 2901-2909.

Nguyen, H., & Santagata, R. (2021). Impact of computer modelling on learning and teaching systems thinking. *Journal of Research in Science Teaching*, *58*(5), 661-688.

Nuhoğlu, H. (2008). *İlköğretim fen ve teknoloji dersinde sistem dinamiği yaklaşımının tutuma, başarıya ve farklı becerilere etkisinin araştırılması*. (Unpublished doctoral thesis). Hacettepe University, Ankara.

Nuhoğlu, H., Göktepe, E ve Yararbaş Ü. (2022). Fen Eğitiminde Disiplinlerarası Yaklaşımlar ve Uygulamaları. Murat Genç ve Harika Özge Aslan (Ed.), *Sistem Düşüncesi* (s. 133-145). Ankara: Nobel Bilimsel Yayınları.

O'Connor, J., & McDermott, I. (1997). *The art of systems thinking* (Vol. 288). San Francisco: Thorsons.

Organization for Economic Co-operation and Development. (2019). *Insights and Interpretations PISA 2018.*Retrieved October 23, 2023 from https://www.oecd.org/pisa/publications/pisa-2018-results.htm

Poçan, S., Altay, B., & Yaşaroğlu, C. (2023). The Effects of Mobile Technology on Learning Performance and Motivation in Mathematics Education. *Education and Information Technologies*, *28*(1), 683-712.

Pulungan, R. R. (2019, February). Analysis of student's misconception in solving system of linear equation in two variables. In *Journal of Physics: Conference Series* (Vol. 1157, No. 4, p. 042113). IOP Publishing.

Putri, R. I. I., & Hiltrimartin, C. (2020, March). Secondary students' higher-order thinking skills in solving PISA-like mathematical tasks. In *Journal of Physics: Conference Series* (Vol. 1480, No. 1, p. 012034). IOP Publishing.

Robinson, W. C. (1973). The limits to growth: A report for the Club of Rome's project on the predicament of mankind by Donella H. Meadows, Dennis L. Meadows, Jergen Randers, and William W. Behrens, III. *Demography*, *10*(2), 289–299. doi: 10.2307/2060819.

Raja, R., & Nagasubramani, P. C. (2018). Impact of modern technology in education. *Journal of Applied and Advanced Research*, *3*(1), 33-35.

Reusser, K. (2000). Success and failure in school mathematics: Effects of instruction and school environment. *European Child & Adolescent Psychiatry*, *9*, 17-26.

Richardson, G. P. (1999). Reflections for the future of system dynamics. *Journal of the operational research society*, *50*(4), 440-449.

Richmond, B. (1994). System dynamics/systems thinking: Let's just get on with it. *System Dynamics Review*, *10*(2-3), 135-157.

Richmond, B. (2010). The thinking in systems thinking: eight critical skills. *Tracing Connections: Voices of Systems Thinkers*, 3-21.

Richmond, B., & Peterson, S. (2001). *An introduction to systems thinking*. Lebanon, NH: High Performance Systems., Incorporated.

Riess, W. ve Mischo, C. (2010). Promoting systems thinking through biology lessons.International Journal of Science Education, *32(6)*,705-725.

Rosana, D., Widodo, E., Setianingsih, W., & Setyawarno, D. (2020). Developing assessment instruments of the PISA model to measure students' problem-solving skills and scientific literacy in junior high schools. *Jurnal Pendidikan Sains Indonesia (Indonesian Journal of Science Education)*, *8*(2), 292-305.

Salado, A., Chowdhury, A. H., & Norton, A. (2019). Systems thinking and mathematical problem solving. *School Science and Mathematics*, *119*(1), 49-58.

Sarsengeldin, M., Satabaldiyev, A., Meirambek, Z., & Guvercin, S. (2013). Interdisciplinary connections and their influence on mathematical education of students. *Procedia-Social and Behavioral Sciences*, *89*, 866-871.

Senge, P. (1990). Peter Senge and the learning organization. *dimension*, 14.

Senge, P. M. (2006). *The fifth discipline: The art and practice of the learning organization*. Broadway Business.

Shirawia, N., Alali, R., Wardat, Y., Tashtoush, M., Saleh, S., & Helali, M. (2023). Logical Mathematical Intelligence and its Impact on the Academic Achievement for Pre-Service Math Teachers. *Journal of Educational and Social Research*, *13*(6), 242-257.

Sistem Düşüncesi Derneği (2021). *Sistem Düşünürünün Alışkanlıkları*. Retrieved April 3, 2024 from https://egitimdesistemdusuncesi.org/nedir/aliskanliklar.php

Sistem Düşüncesi Derneği.(2024, 27 Şubat). *Proje*. Eğitimde Sistem Düşüncesi. https://egitimdesistemdusuncesi.org/nedir/proje.php

Sokolowski, J. A., & Banks, C. M. (Eds.). (2011). *Principles of modeling and simulation: a multidisciplinary approach*. John Wiley & Sons.

Squires, A., Wade, J., Dominick, P., & Gelosh, D. (2011, April). Building a competency taxonomy to guide experience acceleration of lead program systems engineers. In *Proceedings from the Ninth Annual Conference on Systems Engineering Research (CSER), Redondo Beach, CA.*

Massachusetts Institute of Technology Engineering Systems Division. (2002). *System Dynamics: systems thinking and modeling for a complex world.* Retrieved January 29, 2024, from https://dspace.mit.edu/handle/1721.1/102741

Strapasson, A., Ferreira, M., Cruz-Cano, D., Woods, J., do Nascimento Maia Soares, M. P., & da Silva Filho, O. L. (2022). The use of system dynamics for energy and environmental education. *International Journal of Educational Technology in Higher Education*, *19*(1), 5.

System Dynamic Society, (n.d), *System Dynamic Review*. Retrieved December 14, 2023, from https://systemdynamics.org/system-dynamics-review/

Systems Thinking Assossication, (2016), Sytems Thinking Desciptions. Retrieved September 21, 2023, from https://egitimdesistemdusuncesi.org/nedir/tanimlar.php

Şenaras, A. E., & Sezen, H. K. (2017). Sistem düşüncesi. *Journal of Life Economics*, *4*(1), 39-58.

Tashtoush, M. A., Alshunaq, M. M., & Albarakat, A. A. (2020). The Effect of Using Self-Regulated Learning Learning Strategy to Reduce the Level of Mathematics Anxiety among Students of Al-Huson University College. *Jordanian Educational Journal*, *5*(3), 306-329.

Tashtoush, M., Wardat, Y., Al-Shannaq, M., AlAli, R., Saleh, S., & AL-Saud, K. (2023). Conceptual Understanding for Systems of Linear Equations: Difficulties and Challenges. *Information Sciences Letters*, *12*(12), 2491-2503.

Thornton, B., Peltier, G., & Perreault, G. (2004). Systems thinking: A skill to improve student achievement. *The Clearing House: A Journal of Educational Strategies, Issues and Ideas*, *77*(5), 222-230.

Tomlinson, C. A. (2001). *How to differentiate instruction in mixed-ability classrooms*. Ascd.

Turner, G. M. (2008). A comparison of The Limits to Growth with 30 years of reality. *Global environmental change*, *18*(3), 397-411.

Uğurel, I., & Moralı, S. (2008). Matematik ve oyun etkileşimi. *Gazi Üniversitesi Gazi Eğitim Fakültesi Dergisi*, *28*(3), 75-98.

Ulus, B. (2023). *Sistem düşüncesi yaklaşımının Türkçe dersinde ilkokul 2. Sınıf öğrencilerinin okuduklarını anlama becerisine etkisi* (Non-thesis Master's Degree Final Project). MEF University, İstanbul.

U.S. Department of Education. (2009). *Evaluation, and policy development, evaluation of evidence-based practices in online learning: a meta-analysis and review of online learning studies*. Retrieved from https://www2.ed.gov/rschstat/eval/tech/evidence-based-practices/finalreport.pdf

Virginia, A., & Lauren, J. (1997). System Thinking Basics. *From Concepts to Causal Loops, Pegasus Communications Inc*.

Wals, A. E. (2012). *Shaping the education of tomorrow: 2012 full-length report on the UN decade of education for sustainable development*. UNESCO.

Waters Center for Systems Thinking. (n.d). *Who We Are.* Retrieved April 8, 2024 from https://waterscenterst.org/who-we-are?tab=history

Watson-Huggins, J., & Trotman, S. (2019). Gamification and motivation to learn math using technology. *Quarterly Review of Distance Education*, *20*(4), 79-91.

Widada, W., Herawaty, D., Rahman, M. H., Yustika, D., Gusvarini, E. P., & Anggoro, A. F. D. (2020, February). Overcoming the difficulty of understanding systems of linear equations through learning ethnomathematics. In *Journal of Physics: Conference Series* (Vol. 1470, No. 1, p. 012074). IOP Publishing.

World Economic Forum Centre (2023, April 30). *Future of Jobs.* Retrieved September 6, 2023, from https://www.weforum.org/reports/the-future-of-jobs-report-2023/in-full/4-skills-outlook#4-skills-outlook

Yanitsky, O. N. (2020). Prospects of the Interdisciplinary & Systemic Approaches. *Creative Education*, *11*(06), 913.

Yiğitgil, S. (2016). Stok Akış Diyagramı ile Problem Kurup, Çözdük. *Eğitimde Sistem Düşüncesi Yıllığı, (3).*

Zainil, M., Kenedi, A. K., Indrawati, T., & Handrianto, C. (2023). The Influence of a STEM-Based Digital Classroom Learning Model and High-Order Thinking Skills on the 21st-Century Skills of Elementary School Students in Indonesia. *Journal of Education and e-Learning Research*, *10*(1), 29-35.

Zięba, K. (2022). How can systems thinking help us in the COVID-19 crisis? *Knowledge and Process Management*, *29*(3), 221-230.